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(54) Title: SYSTEM AND METHOD OF USING MULTIPLE CORRELATOR RECEIVERS IN AN IMPULSE RADIO SYSTEM

(57) Abstract: A TM-UWB system that utilizes a multiple correlator receiver thereby enabling a scanning receiver, which precisely measures the impulse response of a channel and wherein measurements can be made out to the maximum communications range of a system. Thus, not only capturing ultra-wideband propagation waveforms, but also information on data symbol statistics. Further, multiple correlators enable rake acquisition of pulses and thus faster acquisition, tracking implementations to maintain lock and enable various modulation schemes. Once a tracking correlator is synchronized and locked to an incoming signal, the scanning correlator can sample the received waveform at precise time delays relative to the tracking point. By successively increasing the time delay while sampling the waveform, a complete, time-calibrated picture of the waveform can be collected.

System and Method of Using Multiple Correlator Receivers in an Impulse Radio System

Background of the Invention

Field of the Invention

The present invention generally relates to wireless communications, and more specifically, to a system and a method of using multiple correlators in an impulse radio system for significant system improvements.

Background of the Invention and Related Art

Time Modulated Ultra-Wide Band (TM-UWB), an advanced ultra-wideband RF technology, utilizes short Gaussian monocycle pulses at relatively high pulse repetition frequencies. Typically, pulse durations are less than 1 ns and pulse repetition frequencies exceed 1 MHz. The interval between pulses is not fixed, but is time coded using sequences of random or pseudo-random numbers. This time hopping randomizes the signal in both time and frequency domains. Also, time hopping allows for code division channelization and acts to decorrelate in-band jammers.

Pulse position modulation is used to encode information onto the pulse train. For example, a binary modulation scheme could transmit a monocycle pulse one-quarter of a pulse width early (relative to nominal) to represent a "0" bit and one-quarter of a pulse width late to represent a "1" bit. A single bit or data symbol is typically spread over many pulses. The receiver uses a cross correlation technique (a matched filter that consists of an analog multiplication followed by an integration) to directly convert each RF monocycle into a baseband signal. The output of the correlator (also referred to as a correlation value) is an estimator of the time of arrival of the received pulse plus a noise

component. Multiple correlation values can be coherently combined to combat noise.

In time modulated ultra-wideband radios, processing gain is achieved through two mechanisms. The first mechanism is the low duty cycle of the signal; the correlator provides for a duty cycle processing gain, e.g., a 500 ps pulse transmitted, on average, once every 100 ns, has a duty cycle processing gain of 200 or 23 dB. The second source of processing gain is from coherent addition of correlation samples; for example, coherently combining 1000 pulses yields an additional gain of 1000 or 30 dB. Total processing gain is then the sum of the duty cycle gain and the pulse integration gains.

While it is generally recognized that frequency diversity improves communications link performance within high multipath environments, there is insufficient data to allow definitive comparisons between ultra-wideband and traditional approaches, e.g., frequency hopping and direct sequence spread spectrum.

Traditional instrumentation, such as spectrum analyzers, have limited usage for measuring ultra-wideband signals because at meaningful distances the ultra-wideband signal is below ambient noise and phase information is not available. Thus, as with much of the work done to evaluate the propagation of traditional spread spectrum signals, a special instrumentation system is required to capture ultra-wideband propagation data.

Previously a synchronously triggered digital sampling oscilloscope measurement system to measure propagation within buildings has been used, an approach that works when the ultra-wideband signal is not buried in noise. When ambient signal levels are large, the inability of an oscilloscope to synchronously trigger on the desired signal prevents data acquisition. Thus, it is impossible to use this same instrumentation approach to capture ultra-wideband signals at longer ranges and in urban environments where there are large background signals, e.g., cellular and television emissions.

Clearly, the duality of the frequency and time domains means that existing frequency domain propagation measurements can be translated into the

time domain. Unfortunately, the bandwidth of existing narrowband measurements and the loss of phase information prevents examination of sub-nanosecond scale processes. These limitations prevent the development of definitive channel models for time modulated ultra-wideband signals using narrowband data. Thus, to create useful channel models for time modulated ultra-wideband, extremely fine time resolution is an absolute requirement.

A useful channel model for time modulated ultra-wideband RF would describe:

1) Gross $1/R^n$ attenuation characteristics based on the largest received pulse;

2) The number of time resolvable pulses (paths) and their time and post-correlation amplitude distributions (time dispersion, related to delay spread); and

3) Variability of propagation paths as a function of distance moved (path attenuation due to blockage, related to coherence bandwidth and time).

Additionally, it would be valuable to capture absolute time of arrival for use in estimating the accuracy of any attempts to build geo-ranging systems and the characteristics of noise for the purposes of estimating the impact of various error detection and correction algorithms.

Thus a strong need to overcome the limitations of both traditional instrumentation and the synchronously triggered digital sampling scope instrument and to provide the aforementioned characteristics exist.

Summary of the Invention

Briefly stated, the present invention is a TM-UWB system that utilizes a multiple correlator receiver. The use of a multiple correlator receiver enables such devices as a scanning receiver, which precisely measures the impulse response of a channel and wherein measurements can be made out to the maximum communications range of a system; thus, not only capturing ultra-

wideband propagation waveforms, but also information on data symbol statistics. The data collected from this measurement instrument can be used to create channel models, guide selection of locking algorithms, characterize noise, analyze error correction techniques, and study geo-ranging capabilities.

Further, multiple correlators enable rake acquisition of pulses and thus faster acquisition, tracking implementations to maintain lock and various modulation schemes. By using these new modulation schemes enabled through the use of multiple correlators, increased information about a received pulse can be ascertained. This enables the possibility of vastly improved information transfer rates. Therefore, it is an object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers.

It is another object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers to enable a scanning receiver.

It is still another object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers to enable impulse radio fast acquisitioning.

It is still another object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers to enable impulse radio fast acquisitioning using raking techniques.

It is still another object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers to enable impulse radio multiple correlator tracking.

It is still another object of the present invention to provide an impulse radio system that utilizes multiple correlators in its receivers to enable various modulation techniques.

Brief Description of the Drawings

The present invention is described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or

functionally similar elements. Additionally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears.

FIG. 1A illustrates a representative Gaussian Monocycle waveform in the time domain;

FIG. 1B illustrates the frequency domain amplitude of the Gaussian Monocycle of FIG. 1A;

FIG. 2A illustrates a pulse train comprising pulses as in FIG. 1A;

FIG. 2B illustrates the frequency domain amplitude of the waveform of FIG. 2A;

FIG. 3 illustrates the frequency domain amplitude of a sequence of time coded pulses;

FIG. 4 illustrates a typical received signal and interference signal;

FIG. 5A illustrates a typical geometrical configuration giving rise to multipath received signals;

FIG. 5B illustrates exemplary multipath signals in the time domain;

FIGS 5C - 5E illustrate a signal plot of various multipath environments.

FIGS. 5F illustrates the Rayleigh fading curve associated with non-impulse radio transmissions in a multipath environment.

FIG. 5G illustrates a plurality of multipaths with a plurality of reflectors from a transmitter to a receiver.

FIG. 5H graphically represents signal strength as volts vs. time in a direct path and multipath environment.

FIG. 6 illustrates a representative impulse radio transmitter functional diagram.

FIG. 7 illustrates a representative impulse radio receiver functional diagram.

FIG. 8A illustrates a representative received pulse signal at the input to the correlator.

FIG. 8B illustrates a sequence of representative impulse signals in the correlation process.

FIG. 8C illustrates the potential locus of results as a function of the various potential template time positions.

FIG. 9A illustrates four nodes in an Impulse Radio TDMA linked network and the known distances between each node.

FIG. 9B illustrates the four time slots associated with a four node Impulse Radio TDMA network.

FIG. 10 illustrates a block diagram for the transmitter and multiple correlator scanning receiver, according to an embodiment of the present invention.

FIG. 11 illustrates a corresponding impulse radio transmitter.

FIG. 12 is an impulse response of room with 4 meters of separation and with one intervening sheet rock and metal stud wall between the transmitter and receiver.

FIG. 13 illustrates the output of the tracking correlator for a 250 point scan.

FIGS. 14 and 15 show the impulse response measurements for two different in-building scans. FIG. 14 is the first scan is at a range of approximately 4 meters through a single wall (sheet rock over metal studs). FIG 15 is the second scan at a range of 21 meters through five walls of similar construction.

FIG. 16 shows the amplitude vs. range of the three largest correlations where data was taken at each location. The "+" signs indicate the coherent sum of the top ten correlation values as might be obtained from a variable tap rake receiver design.

FIG. 17 illustrates the time of arrival of the three largest correlations at each location where data was taken. The largest correlation is marked with "o", the second largest with "+', and the third largest with "*".

FIG. 18 is an overview block diagram illustrating an eight correlators receiver.

FIG. 19 more particularly sets forth the correlator configuration within a digital impulse radio architecture.

FIG. 20 illustrates a distinct timer configuration used in a multiple correlator receiver.

FIG. 21 is yet another distinct configuration of a multiple correlator receiver wherein slaved correlators are utilized and driven by the same timer as the master correlator with a delay therebetween.

Detailed Description of the Embodiments

Overview of the Invention

The present invention will now be described more fully in detail with reference to the accompanying drawings, in which the preferred embodiments of the invention are shown. This invention should not, however, be construed as limited to the embodiments set forth herein; rather, they are provided so that this disclosure will be thorough and complete and will fully convey the scope of the invention to those skilled in art. Like numbers refer to like elements throughout.

Recent advances in communications technology have enabled an emerging, revolutionary ultra wideband technology (UWB) called impulse radio communications systems (hereinafter called impulse radio). To better understand the benefits of impulse radio to the present invention, the following review of impulse radio follows Impulse radio was first fully described in a series of patents, including U.S. Patent Nos. 4,641,317 (issued February 3, 1987), 4,813,057 (issued March 14, 1989), 4,979,186 (issued December 18, 1990) and 5,363,108 (issued November 8, 1994) to Larry W. Fullerton. A second generation of impulse radio patents include U.S. Patent Nos. 5,677,927 (issued October 14, 1997), 5,687,169 (issued November 11, 1997) and 5,832,035 (issued November 3, 1998) to Fullerton *et al.*

As background, various uses of impulse radio systems are described in U.S. Patent Application No. 09/332,502 (Attorney Docket No. 1659.0720000), entitled, *"System and Method for Intrusion Detection Using a Time Domain Radar Array,"* and U.S. Patent Application No. 09/332,503 (Attorney Docket No. 1659.0670000), entitled, *"Wide Area Time Domain Radar Array,"* both filed on

June 14, 1999 and both of which are assigned to the assignee of the present invention.

Impulse Radio Basics

This section is directed to technology basics and provides the reader with an introduction to impulse radio concepts, as well as other relevant aspects of communications theory. This section includes subsections relating to waveforms, pulse trains, coding for energy smoothing and channelization, modulation, reception and demodulation, interference resistance, processing gain, capacity, multipath and propagation, distance measurement, and qualitative and quantitative characteristics of these concepts. It should be understood that this section is provided to assist the reader with understanding the present invention, and should not be used to limit the scope of the present invention.

Impulse radio refers to a radio system based on short, low duty cycle pulses. An ideal impulse radio waveform is a short Gaussian monocycle. As the name suggests, this waveform attempts to approach one cycle of radio frequency (RF) energy at a desired center frequency. Due to implementation and other spectral limitations, this waveform may be altered significantly in practice for a given application. Most waveforms with enough bandwidth approximate a Gaussian shape to a useful degree.

Impulse radio can use many types of modulation, including AM, time shift (also referred to as pulse position) and M-ary versions. The time shift method has simplicity and power output advantages that make it desirable. In this document, the time shift method is used as an illustrative example.

In impulse radio communications, the pulse-to-pulse interval can be varied on a pulse-by-pulse basis by two components: an information component and a pseudo-random code component. Generally, conventional spread spectrum systems make use of pseudo-random codes to spread the normally narrow band information signal over a relatively wide band of frequencies. A conventional spread spectrum receiver correlates these signals to retrieve the original

information signal. Unlike conventional spread spectrum systems, the pseudo-random code for impulse radio communications is not necessary for energy spreading because the monocycle pulses themselves have an inherently wide bandwidth. Instead, the pseudo-random code is used for channelization, energy smoothing in the frequency domain, resistance to interference, and reducing the interference potential to nearby receivers.

The impulse radio receiver is typically a direct conversion receiver with a cross correlator front end in which the front end coherently converts an electromagnetic pulse train of monocycle pulses to a baseband signal in a single stage. The baseband signal is the basic information signal for the impulse radio communications system. It is often found desirable to include a subcarrier with the baseband signal to help reduce the effects of amplifier drift and low frequency noise. The subcarrier that is typically implemented alternately reverses modulation according to a known pattern at a rate faster than the data rate. This same pattern is used to reverse the process and restore the original data pattern just before detection. This method permits alternating current (AC) coupling of stages, or equivalent signal processing to eliminate direct current (DC) drift and errors from the detection process. This method is described in detail in U.S. Patent No. 5,677,927 to Fullerton *et al.*

In impulse radio communications utilizing time shift modulation, each data bit typically time position modulates many pulses of the periodic timing signal. This yields a modulated, coded timing signal that comprises a train of identically shaped pulses for each single data bit. The impulse radio receiver integrates multiple pulses to recover the transmitted information.

Waveforms

Impulse radio refers to a radio system based on short, low duty cycle pulses. In the widest bandwidth embodiment, the resulting waveform approaches one cycle per pulse at the center frequency. In more narrow band embodiments, each pulse consists of a burst of cycles usually with some spectral shaping to

control the bandwidth to meet desired properties such as out of band emissions or in-band spectral flatness, or time domain peak power or burst off time attenuation.

For system analysis purposes, it is convenient to model the desired waveform in an ideal sense to provide insight into the optimum behavior for detail design guidance. One such waveform model that has been useful is the Gaussian monocycle as shown in Fig. 1A. This waveform is representative of the transmitted pulse produced by a step function into an ultra-wideband antenna. The basic equation normalized to a peak value of 1 is as follows:

$$f_{mono}(t) = \sqrt{e}\left(\frac{t}{\sigma}\right)\frac{-t^2}{e^{2\sigma^2}}$$

Where,

σ is a time scaling parameter,

t is time,

$fmono(t)$ is the waveform voltage, and

e is the natural logarithm base.

The frequency domain spectrum of the above waveform is shown in FIG. 1B. The corresponding equation is:

$$F_{mono}(f) = (2\pi)^{\frac{3}{2}}\sigma f e^{-2(\pi\sigma f)^2}$$

The center frequency (f_c), or frequency of peak spectral density is:

$$f_c = \frac{1}{2\pi\sigma}$$

These pulses, or bursts of cycles, may be produced by methods described in the patents referenced above or by other methods that are known to one of ordinary skill in the art. Any practical implementation will deviate from the ideal

mathematical model by some amount. In fact, this deviation from ideal may be substantial and yet yield a system with acceptable performance. This is especially true for microwave implementations, where precise waveform shaping is difficult to achieve. These mathematical models are provided as an aid to describing ideal operation and are not intended to limit the invention. In fact, any burst of cycles that adequately fills a given bandwidth and has an adequate on-off attenuation ratio for a given application will serve the purpose of this invention.

A Pulse Train

Impulse radio systems can deliver one or more data bits per pulse; however, impulse radio systems more typically use pulse trains, not single pulses, for each data bit. As described in detail in the following example system, the impulse radio transmitter produces and outputs a train of pulses for each bit of information.

Prototypes built by the inventors have pulse repetition frequencies including 0.7 and 10 megapulses per second (Mpps, where each megapulse is 10^6 pulses). Figs. 2A and 2B are illustrations of the output of a typical 10 Mpps system with uncoded, unmodulated, 0.5 nanosecond (ns) pulses 102. Fig. 2A shows a time domain representation of this sequence of pulses 102. Fig 2B, which shows 60 MHZ at the center of the spectrum for the waveform of Fig. 2A, illustrates that the result of the pulse train in the frequency domain is to produce a spectrum comprising a set of lines 204 spaced at the frequency of the 10 Mpps pulse repetition rate. When the full spectrum is shown, the envelope of the line spectrum follows the curve of the single pulse spectrum 104 of Fig. 1B. For this simple uncoded case, the power of the pulse train is spread among roughly two hundred comb lines. Each comb line thus has a small fraction of the total power and presents much less of an interference problem to receiver sharing the band.

It can also be observed from Fig. 2A that impulse radio systems typically have very low average duty cycles resulting in average power significantly lower

than peak power. The duty cycle of the signal in the present example is 0.5%, based on a 0.5 ns pulse in a 100 ns interval.

Coding for Energy Smoothing and Channelization

For high pulse rate systems, it may be necessary to more finely spread the spectrum than is achieved by producing comb lines. This may be done by pseudo-randomly positioning each pulse relative to its nominal position.

Fig. 3 is a plot illustrating the impact of a pseudo-noise (PN) code dither on energy distribution in the frequency domain (A pseudo-noise, or PN code is a set of time positions defining the pseudo-random positioning for each pulse in a sequence of pulses). Fig. 3, when compared to Fig. 2B, shows that the impact of using a PN code is to destroy the comb line structure and spread the energy more uniformly. This structure typically has slight variations which are characteristic of the specific code used.

The PN code also provides a method of establishing independent communication channels using impulse radio. PN codes can be designed to have low cross correlation such that a pulse train using one code will seldom collide on more than one or two pulse positions with a pulses train using another code during any one data bit time. Since a data bit may comprise hundreds of pulses, this represents a substantial attenuation of the unwanted channel.

Modulation

Any aspect of the waveform can be modulated to convey information. Amplitude modulation, phase modulation, frequency modulation, time shift modulation and M-ary versions of these have been proposed. Both analog and digital forms have been implemented. Of these, digital time shift modulation has been demonstrated to have various advantages and can be easily implemented using a correlation receiver architecture.

Digital time shift modulation can be implemented by shifting the coded time position by an additional amount (that is, in addition to PN code dither) in response to the information signal. This amount is typically very small relative to the PN code shift. In a 10 Mpps system with a center frequency of 2 GHz., for example, the PN code may command pulse position variations over a range of 100 ns; whereas, the information modulation may only deviate the pulse position by 150 ps.

Thus, in a pulse train of *n* pulses, each pulse is delayed a different amount from its respective time base clock position by an individual code delay amount plus a modulation amount, where *n* is the number of pulses associated with a given data symbol digital bit.

Modulation further smoothes the spectrum, minimizing structure in the resulting spectrum.

Reception and Demodulation

Clearly, if there were a large number of impulse radio users within a confined area, there might be mutual interference. Further, while the PN coding minimizes that interference, as the number of users rises, the probability of an individual pulse from one user's sequence being received simultaneously with a pulse from another user's sequence increases. Impulse radios are able to perform in these environments, in part, because they do not depend on receiving *every* pulse. The impulse radio receiver performs a correlating, synchronous receiving function (at the RF level) that uses a statistical sampling and combining of many pulses to recover the transmitted information.

Impulse radio receivers typically integrate from 1 to 1000 or more pulses to yield the demodulated output. The optimal number of pulses over which the receiver integrates is dependent on a number of variables, including pulse rate, bit rate, interference levels, and range.

Interference Resistance

Besides channelization and energy smoothing, the PN coding also makes impulse radios highly resistant to interference from all radio communications systems, including other impulse radio transmitters. This is critical as any other signals within the band occupied by an impulse signal potentially interfere with the impulse radio. Since there are currently no unallocated bands available for impulse systems, they must share spectrum with other conventional radio systems without being adversely affected. The PN code helps impulse systems discriminate between the intended impulse transmission and interfering transmissions from others. Fig. 4 illustrates the result of a narrow band sinusoidal interference signal 402 overlaying an impulse radio signal 404. At the impulse radio receiver, the input to the cross correlation would include the narrow band signal 402, as well as the received ultrawide-band impulse radio signal 404. The input is sampled by the cross correlator with a PN dithered template signal 406. Without PN coding, the cross correlation would sample the interfering signal 402 with such regularity that the interfering signals could cause significant interference to the impulse radio receiver. However, when the transmitted impulse signal is encoded with the PN code dither (and the impulse radio receiver template signal 406 is synchronized with that identical PN code dither) the correlation samples the interfering signals pseudo-randomly. The samples from the interfering signal add incoherently, increasing roughly according to square root of the number of samples integrated; whereas, the impulse radio samples add coherently, increasing directly according to the number of samples integrated. Thus, integrating over many pulses overcomes the impact of interference.

Processing Gain

Impulse radio is resistant to interference because of its large processing gain. For typical spread spectrum systems, the definition of processing gain, which quantifies the decrease in channel interference when wide-band

communications are used, is the ratio of the bandwidth of the channel to the bit rate of the information signal. For example, a direct sequence spread spectrum system with a 10 kHz information bandwidth and a 10 MHZ channel bandwidth yields a processing gain of 1000 or 30 dB. However, far greater processing gains are achieved with impulse radio systems, where for the same 10 KHz information bandwidth is spread across a much greater 2 GHz. channel bandwidth, the theoretical processing gain is 200,000 or 53 dB.

Capacity

It has been shown theoretically, using signal to noise arguments, that thousands of simultaneous voice channels are available to an impulse radio system as a result of the exceptional processing gain, which is due to the exceptionally wide spreading bandwidth.

For a simplistic user distribution, with N interfering users of equal power equidistant from the receiver, the total interference signal to noise ratio as a result of these other users can be described by the following equation:

$$V^2_{tot} = \frac{N\sigma^2}{\sqrt{Z}}$$

Where V^2_{tot} is the total interference signal to noise ratio variance, at the receiver;

N is the number of interfering users;

σ^2 is the signal to noise ratio variance resulting from one of the interfering signals with a single pulse cross correlation; and

Z is the number of pulses over which the receiver integrates to recover the modulation.

This relationship suggests that link quality degrades gradually as the number of simultaneous users increases. It also shows the advantage of

integration gain. The number of users that can be supported at the same interference level increases by the square root of the number of pulses integrated.

Multipath and Propagation

One of the striking advantages of impulse radio is its resistance to multipath fading effects. Conventional narrow band systems are subject to multipath through the Rayleigh fading process, where the signals from many delayed reflections combine at the receiver antenna according to their seemingly random relative phases. This results in possible summation or possible cancellation, depending on the specific propagation to a given location. This situation occurs where the direct path signal is weak relative to the multipath signals, which represents a major portion of the potential coverage of a radio system. In mobile systems, this results in wild signal strength fluctuations as a function of distance traveled, where the changing mix of multipath signals results in signal strength fluctuations for every few feet of travel.

Impulse radios, however, can be substantially resistant to these effects. Impulses arriving from delayed multipath reflections typically arrive outside of the correlation time and thus can be ignored. This process is described in detail with reference to FIGs. 5A and 5B. In FIG. 5A, three propagation paths are shown. The direct path representing the straight line distance between the transmitter and receiver is the shortest. Path 1 represents a grazing multipath reflection, which is very close to the direct path. Path 2 represents a distant multipath reflection. Also shown are elliptical (or, in space, ellipsoidal) traces that represent other possible locations for reflections with the same time delay.

FIG. 5B represents a time domain plot of the received waveform from this multipath propagation configuration. This figure comprises three doublet pulses as shown in FIG. 1A. The direct path signal is the reference signal and represents the shortest propagation time. The path 1 signal is delayed slightly and actually overlaps and enhances the signal strength at this delay value. Note that the

reflected waves are reversed in polarity. The path 2 signal is delayed sufficiently that the waveform is completely separated from the direct path signal. If the correlator template signal is positioned at the direct path signal, the path 2 signal will produce no response. It can be seen that only the multipath signals resulting from very close reflectors have any effect on the reception of the direct path signal. The multipath signals delayed less than one quarter wave (one quarter wave is about 1.5 inches, or 3.5cm at 2 GHz center frequency) are the only multipath signals that can attenuate the direct path signal. This region is equivalent to the first Fresnel zone familiar to narrow band systems designers. Impulse radio, however, has no further nulls in the higher Fresnel zones. The ability to avoid the highly variable attenuation from multipath gives impulse radio significant performance advantages.

Fig 5A illustrates a typical multipath situation, such as in a building, where there are many reflectors 5A04, 5A05 and multiple propagation paths 5A02, 5A01. In this figure, a transmitter TX 5A06 transmits a signal which propagates along the multiple propagation paths 5A02, 5A04 to receiver RX 5A08, where the multiple reflected signals are combined at the antenna.

FIG. 5B illustrates a resulting typical received composite pulse waveform resulting from the multiple reflections and multiple propagation paths 5A01, 5A02. In this figure, the direct path signal 5A01 is shown as the first pulse signal received. The multiple reflected signals ("multipath signals", or "multipath") comprise the remaining response as illustrated.

FIGs. 5C, 5D, and 5E represent the received signal from a TM-UWB transmitter in three different multipath environments. These figures are not actual signal plots, but are hand drawn plots approximating typical signal plots. FIG. 5C illustrates the received signal in a very low multipath environment. This may occur in a building where the receiver antenna is in the middle of a room and is one meter from the transmitter. This may also represent signals received from some distance, such as 100 meters, in an open field where there are no objects to produce reflections. In this situation, the predominant pulse is the first received pulse and the multipath reflections are too weak to be significant. FIG. 5D

illustrates an intermediate multipath environment. This approximates the response from one room to the next in a building. The amplitude of the direct path signal is less than in FIG. 5C and several reflected signals are of significant amplitude. (Note that the scale has been increased to normalize the plot.) FIG. 5E approximates the response in a severe multipath environment such as: propagation through many rooms; from corner to corner in a building; within a metal cargo hold of a ship; within a metal truck trailer; or within an intermodal shipping container. In this scenario, the main path signal is weaker than in FIG. 5D. (Note that the scale has been increased again to normalize the plot.) In this situation, the direct path signal power is small relative to the total signal power from the reflections.

An impulse radio receiver in accordance with the present invention can receive the signal and demodulate the information using either the direct path signal or any multipath signal peak having sufficient signal to noise ratio. Thus, the impulse radio receiver can select the strongest response from among the many arriving signals. In order for the signals to cancel and produce a null at a given location, dozens of reflections would have to be cancelled simultaneously and precisely while blocking the direct path – a highly unlikely scenario. This time separation of mulitipath signals together with time resolution and selection by the receiver permit a type of time diversity that virtually eliminates cancellation of the signal. In a multiple correlator rake receiver, performance is further improved by collecting the signal power from multiple signal peaks for additional signal to noise performance.

Where the system of FIG. 5A is a narrow band system and the delays are small relative to the data bit time, the received signal is a sum of a large number of sine waves of random amplitude and phase. In the idealized limit, the resulting envelope amplitude has been shown to follow a Rayleigh probability distribution as follows:

$$p(r) = \frac{1}{\sigma^2}\exp\left(\frac{-r^2}{2\sigma^2}\right)$$

where r is the envelope amplitude of the combined multipath signals, and $2\sigma^2$ is the RMS power of the combined mulitpath signals.

This distribution shown in FIG. 5F. It can be seen in FIG. 5F that 10% of the time, the signal is more than 16 dB attenuated. This suggests that 16 dB fade margin is needed to provide 90% link availability. Values of fade margin from 10 to 40 dB have been suggested for various narrow band systems, depending on the required reliability. This characteristic has been the subject of much research and can be partially improved by such techniques as antenna and frequency diversity, but these techniques result in additional complexity and cost.

In a high multipath environment such as inside homes, offices, warehouses, automobiles, trailers, shipping containers, or outside in the urban canyon or other situations where the propagation is such that the received signal is primarily scattered energy, impulse radio, according to the present invention, can avoid the Rayleigh fading mechanism that limits performance of narrow band systems. This is illustrated in FIG. 5G and 5H in a transmit and receive system in a high multipath environment 5G00, wherein the transmitter 5G06 transmits to receiver 5G08 with the signals reflecting off reflectors 5G03 which form multipaths 5G02. The direct path is illustrated as 5G01 with the signal graphically illustrated at 5H02, with the vertical axis being the signal strength in volts and horizontal axis representing time in nanoseconds. Multipath signals are graphically illustrated at 5H04.

Distance Measurement

Important for positioning, impulse systems can measure distances to extremely fine resolution because of the absence of ambiguous cycles in the waveform. Narrow band systems, on the other hand, are limited to the modulation envelope and cannot easily distinguish precisely which RF cycle is associated with each data bit because the cycle-to-cycle amplitude differences are so small they are masked by link or system noise. Since the impulse radio waveform has no multi-cycle ambiguity, this allows positive determination of the waveform position to less than a wavelength - potentially, down to the noise floor

of the system. This time position measurement can be used to measure propagation delay to determine link distance, and once link distance is known, to transfer a time reference to an equivalently high degree of precision. The inventors of the present invention have built systems that have shown the potential for centimeter distance resolution, which is equivalent to about 30 ps of time transfer resolution. See, for example, commonly owned, co-pending applications 09/045,929, filed March 23, 1998, titled "Ultrawide-Band Position Determination System and Method", and 09/083,993, filed May 26, 1998, titled "System and Method for Distance Measurement by Inphase and Quadrature Signals in a Radio System."

In addition to the methods articulated above, impulse radio technology along with Time Division Multiple Access algorithms and Time Domain packet radios can achieve geo-positioning capabilities in a radio network. This geo-positioning method allows ranging to occur within a network of radios without the necessity of a full duplex exchange among every pair of radios.

FIG. 9A illustrates an example of a four slot TDMA network 90A. We begin with all radios off the air. As the first radio, 92A, comes on, it pauses to listen to the current network traffic. After a reasonable delay, it powers on and, having heard no other traffic, takes control of the first slot shown in FIG. 9B as 92B. While online, it will periodically send a hello request containing identifying information showing it owns slot 1. Although the network is considered adhoc, the radio that owns the first TDMA slot has some unique responsibilities.

Radio B, 94A, powers up next and begins to listen to network traffic. It notes that Radio A, 92A, is on the air in the first slot. Radio B, 94A, acquires slot 2, 94B, and transmits a hello request at the slot two position 2, 94B. The hello request prompts an exchange with Radio A, 92A, as soon as his slot comes available. Radio A transmits a packet that will result in the acquisition of two pieces of information. Radio A, 92A, sends a SYNC packet containing a request for an immediate acknowledgement. Radio B, 94A, is thereby given permission to respond during Radio A's slot time. Radio B, 94A, transmits a SYNC ACK

packet in return. Radio A, 92A, then calculates the distance to Radio B, 94A, and properly adjusts the synchronization clock for the distance and sends the current time, adjusted for distance, to Radio B, 94A. At this point Radio A's, 92A, clock is synchronized with Radio B, 94A. Once this occurs, any time Radio A, 92A, transmits, Radio B, 94A, is capable of calculating the distance to Radio A, 92A, without a full duplex exchange. Also any time Radio B, 94A, transmits, Radio A, 94A, is capable of calculating the distance to Radio B, 94A.

Through periodic SYNC packets to radio C, 98A, and radio D, 96A, on the network, clock synchronization could be maintained throughout the entire network of radios. Assuming that radio A, 92A, radio B, 94A, radio C, 98A and radio D, 96A, always transmit packets at the immediate start of their slot times 92B, 94B, 96B, and 98B, this system would allow all radios on a network to immediately calculate the distance to any other radio on the network whenever a radio transmitted a packet.

Traditional Transceiver Implementation

Transmitter

An exemplary embodiment of an impulse radio transmitter 602 of an impulse radio communication system having one subcarrier channel will now be described with reference to Fig. 6.

The transmitter 602 comprises a time base 604 that generates a periodic timing signal 606. The time base 604 typically comprises a voltage controlled oscillator (VCO), or the like, having a high timing accuracy and low jitter, on the order of picoseconds (ps). The voltage control to adjust the VCO center frequency is set at calibration to the desired center frequency used to define the transmitter's nominal pulse repetition rate. The periodic timing signal 606 is supplied to a precision timing generator 608.

The precision timing generator 608 supplies synchronizing signals 610 to the code source 612 and utilizes the code source output 614 together with an

internally generated subcarrier signal (which is optional) and an information signal 616 to generate a modulated, coded timing signal 618.

The code source 612 comprises a storage device such as a random access memory (RAM), read only memory (ROM), or the like, for storing suitable PN codes and for outputting the PN codes as a code signal 614. Alternatively, maximum length shift registers or other computational means can be used to generate the PN codes.

An information source 620 supplies the information signal 616 to the precision timing generator 608. The information signal 616 can be any type of intelligence, including digital bits representing voice, data, imagery, or the like, analog signals, or complex signals.

A pulse generator 622 uses the modulated, coded timing signal 618 as a trigger to generate output pulses. The output pulses are sent to a transmit antenna 624 via a transmission line 626 coupled thereto. The output pulses are converted into propagating electromagnetic pulses by the transmit antenna 624. In the present embodiment, the electromagnetic pulses are called the emitted signal, and propagate to an impulse radio receiver 702, such as shown in Fig. 7, through a propagation medium, such as air, in a radio frequency embodiment. In a preferred embodiment, the emitted signal is wide-band or ultrawide-band, approaching a monocycle pulse as in Fig. 1A. However, the emitted signal can be spectrally modified by filtering of the pulses. This filtering will usually cause each monocycle pulse to have more zero crossings (more cycles) in the time domain. In this case, the impulse radio receiver can use a similar waveform as the template signal in the cross correlator for efficient conversion.

Receiver

An exemplary embodiment of an impulse radio receiver 702 (hereinafter called the receiver) for the impulse radio communication system is now described with reference to Fig. 7. More specifically, the system illustrated in Fig. 7 is for

reception of digital data wherein one or more pulses are transmitted for each data bit.

The receiver 702 comprises a receive antenna 704 for receiving a propagated impulse radio signal 706. A received signal 708 from the receive antenna 704 is coupled to a cross correlator or sampler 710 to produce a baseband output 712. The cross correlator or sampler 710 includes multiply and integrate functions together with any necessary filters to optimize signal to noise ratio.

The receiver 702 also includes a precision timing generator 714, which receives a periodic timing signal 716 from a receiver time base 718. This time base 718 is adjustable and controllable in time, frequency, or phase, as required by the lock loop in order to lock on the received signal 708. The precision timing generator 714 provides synchronizing signals 720 to the code source 722 and receives a code control signal 724 from the code source 722. The precision timing generator 714 utilizes the periodic timing signal 716 and code control signal 724 to produce a coded timing signal 726. The template generator 728 is triggered by this coded timing signal 726 and produces a train of template signal pulses 730 ideally having waveforms substantially equivalent to each pulse of the received signal 708. The code for receiving a given signal is the same code utilized by the originating transmitter 602 to generate the propagated signal 706. Thus, the timing of the template pulse train 730 matches the timing of the received signal pulse train 708, allowing the received signal 708 to be synchronously sampled in the correlator 710. The correlator 710 ideally comprises a multiplier followed by a short-term integrator to sum the multiplier product over the pulse interval. Further examples and details of correlation and sampling processes can be found in the above-reference commonly owned patents and commonly owned and copending U.S. Patent Application No. 09/356,384, filed July 16, 1999, entitled "Baseband Signal Converter Device for a Wideband Impulse Radio Receiver."

The output of the correlator 710, also called a baseband signal 712, is coupled to a subcarrier demodulator 732, which demodulates the subcarrier information signal from the subcarrier. The purpose of the optional subcarrier

process, when used, is to move the information signal away from DC (zero frequency) to improve immunity to low frequency noise and offsets. The output of the subcarrier demodulator 732 is then filtered or integrated in a pulse summation stage 734. The pulse summation stage produces an output representative of the sum of a number of pulse signals comprising a single data bit. The output of the pulse summation stage 734 is then compared with a nominal zero (or reference) signal output in a detector stage 738 to determine an output signal 739 representing an estimate of the original information signal 616.

The baseband signal 712 is also input to a lowpass filter 742 (also referred to as lock loop filter 742). A control loop comprising the lowpass filter 742, time base 718, precision timing generator 714, template generator 728, and correlator 710 is used to generate a filtered error signal 744. The filtered error signal 744 provides adjustments to the adjustable time base 718 to time position the periodic timing signal 726 in relation to the position of the received signal 708.

In a transceiver embodiment, substantial economy can be achieved by sharing part or all of several of the functions of the transmitter 602 and receiver 702. Some of these include the time base 718, precision timing generator 714, code source 722, antenna 704, and the like.

FIGS. 8A, 8B and 9 illustrate the cross correlation process and the correlation function. Fig. 8A shows the waveform of a template signal. Fig. 8B shows the waveform of a received impulse radio signal at a set of several possible time offsets. Fig. 9 represents the output of the correlator (multiplier and short time integrator) for each of the time offsets of Fig. 8B. Thus, this graph, Fig. 9, does not show a waveform that is a function of time, but rather a function of time-offset, i.e., for any given pulse received, there is only one corresponding point which is applicable on this graph. This is the point corresponding to the time offset of the template signal used to receive that pulse.

Further examples and details of subcarrier processes and precision timing can be found described in Patent 5,677,927, entitled "Ultrawide-band communication system and method", and commonly owned co-pending

application 09/146,524, filed September 3, 1998, titled "Precision Timing Generator System and Method."

Novel Tranceiver Implementation

With the development of precision, low noise synchronous programmable time delay integrated circuits, it is now feasible to build customized time modulated ultra-wideband systems that measure propagation and enable more accurate analysis and capture of incoming waveforms utilizing multiple correlators. Figure 10 illustrates at 1000 a block diagram for the multiple correlator scanning receiver. FIG. 11 illustrates at 1100 a corresponding impulse radio transmitter. In this implementation, the transmitter emits a 500 ps (measured trough to peak) ultra-wideband pulse at a 10 MHz pulse repetition frequency. Figure 12 shows the output of the scanning receiver when it scans a single transmitted pulse with amplitude 1204 on the vertical axis and time 1202 on the horizontal axis. This measurement shows the filtering impact of the receive antenna, the correlation process, and that the transmitted pulse was filtered to reduce emissions below 1 GHz.

The present embodiment illustrates a scanning receiver comprising two correlators1020, 1030 controlled by two timing systems 1015 and 1085. However, it is understood that any number of correlators (as illustrated hereinafter) can be used to achieve particular correlation results. One of the correlators is a tracking correlator 1020, which varies the phase of its internal coded template until it synchronizes with and is able to track the received pulse train. Any offset between the transmitted pulse repetition frequency and the receiver's internal pulse repetition frequency is detected as an error voltage in the correlation lock loop. Correlation lock loop as used in TM-UWB is described fully in U.S. Patent Application Number 5,832,035 entitled, "Fast Locking Mechanism for Channelized Ultrawide-Band Communications." Correlation Lock loop provides for acquisition and lock of an impulse radio signal.

This error in the correlation lock loop is corrected by synthesizing a frequency offset in the pseudo-random time hopping word 1080. This adjustment ensures the receiver's clock is within approximately 20 ps RMS of the received signal.

Once the tracking correlator 1020 is synchronized and locked to the incoming signal, the scanning correlator 1030 can sample the received waveform at precise time delays relative to the tracking point. By successively increasing the time delay while sampling the waveform, a complete, time-calibrated picture of the waveform can be collected. Also, scanning correlator 1030 can scan prior to the tracking correlator, thus the tracking correlator will be delayed in respect to the scanning correlator. Hence, the wave form information of FIG. 12 (with the Y-axis representing amplitude 1204 and X-axis representing correlator time delay 1202) can be accurately ascertained.

At the same time that waveform data is being captured, samples from the tracking correlator 1020 are also being collected. Samples from the tracking correlator represent integrated, demodulated data symbols prior to processing by the symbol decision logic. Samples from the scanning correlator 1030 and tracking correlator 1020 are collected in pairs so that events in the waveform sample set are time correlated with events in the data symbol set.

Although it is understood that any means of control can be utilized, in this embodiment, control of the system and data storage is provided by a Personal Computer or the like externally connected to the scanning receiver 1000. Several parameters can be varied when capturing a waveform. The scanning correlator 1030 can dwell at a time position for a specified number of pulses, allowing the baseband signal processor 1050 to integrate samples and minimize distortion due to noise. Sample time steps as small as 3.052 ps can be specified, but more typical step sizes are around 60 ps. Time delays of up to 13 ms before or after the tracking point can be specified for start of the waveform capture.

Functionally, and specifically in this embodiment, the incoming impulse RF signal is received via ultra wide band antenna 1010. The signal is split in power splitter 1025 thereby being split among the designed number of correlators.

In this case there are two correlators (tracking correlator 1020 and scanning correlator 1030). The tracking correlator 1020 is triggered by a programmable synchronous time delay 1015 driven by reference clock 1035. The scanning correlator 1030 is triggered by synchronous programmable time delay 1085 which can be driven by the same reference clock 1035. The output of the tracking correlator passes to analog to digital converter 1040 with the digital signal passing to baseband signal processing 1050. The scanning correlator output also passes to analog to digital converter 1045 for input into baseband signal processing 1050.

FIG. 11 illustrates one possible impulse radio transmitter 1100 for transmission of the RF pulses received by the multiple correlator impulse radio receiver 1000. Baseband signal processor 1106 transmits PN delay word 1107 to synchronous programmable time delay 1110, which is driven by reference clock 1108. The output of synchronous programmable time delay 1110 passes to pulse generator 1104 for transmission by ultrawide band antenna 1102.

There are a number of different RF front-end options which are defined by the configuration of the correlation circuits. The correlation function can be implemented in a custom silicon-germanium monolithic integrated circuit which has a single RF input and three independently triggered correlator circuits. One option uses a single integrated circuit for both the tracking and scanning function, providing a single RF input for both functions. Another option uses separate integrated circuits for the tracking and scanning functions, providing independent RF inputs and therefore separate antennas for tracking and scanning. Fixing the location of the tracking channel antenna creates a fixed time reference for the scanning channel, allowing the performance of antenna arrays to be estimated.

The ability of the scanning receiver 1000 to capture data symbols in parallel with waveform data allows it to be used not only for propagation studies but also as a complete link budget analysis tool.

As a propagation tool, the scanning receiver 1000 can be used to measure the impulse response of the environment between any two locations within the communication range of the radio link. In conjunction with application specific

requirements, the response data can guide the selection of signal acquisition and tracking algorithms. For environments with significant multipath effects, it allows estimation of the marginal value of additional correlators for rake receiver applications. As used herein, rake receiver means utilizing a plurality of correlators simultaneously to improve acquisition and lock. Also, if the locations at which measurements are taken are closely spaced, i.e., the antenna is moved less than a pulse width between scans, then individual paths may be analyzed for amplitude fluctuations.

Because data capture is synchronized to always start at the same phase of the bit error test pattern, the user has a priori knowledge of the bit sequence and can compare expected data symbols to actual received symbols. This allows characterization of bit errors, guiding selection of error detection and correction techniques.

Symbol data captured from the tracking channel can be used to calculate the signal to noise ratio for the tracking point. Because the scanning channel is time-calibrated to the tracking channel, the location of the tracking point on the scanned waveform is known. The amplitude ratio of the actual tracking point to other potential tracking points on the waveform can be used to determine the achievable SNR for all other paths. This allows the benefit of coherent (rake) combining of multiple signal paths to be estimated.

Figure 13 illustrates the output of the tracking correlator for a 250 point scan. The Y-Axis 1302 is the amplitude of the voltage as represented by a binary count and the X-Axis 1310 is the sample point number. In this case there is little noise in the channel, since both the zero bits mean 1312 and the ones bit mean 1304 are at least four times the standard deviation away from the zero threshold 1308. Each of the tracking channel samples occurs as the scanning correlator dwells on a single point in time. Thus, each tracking correlator sample is a measure of the ambient noise during the scan. The noise characteristics 1318 mean for the "ones" are shown at 1316 and the mean for the "zeros" are shown at 1314.

Illustrating the importance of determining waveform variations, FIGS. 14 and 15 show the impulse response measurements for two different in-building scans. FIG. 14 is the first scan is at a range of approximately 4 meters through a single wall (sheet rock over metal studs) with the Y-Axis 1402 representing Amplitude of the voltage as represented by a binary count and the X-Axis 1404 representing correlator time delay.

FIG 15 is the second scan, again with the Y-Axis 1502 representing the amplitude of the voltage as represented by a binary count and the X-Axis 1504 representing correlator time delay, at a range of 21 meters through five walls of similar construction (i.e. sheet rock over metal studs). From these scans it becomes possible to evaluate the delay spread and an estimate of the number and quality of signal paths.

As mentioned above, the present scanning and tracking multiple correlator configuration can ascertain path characteristics. FIG. 16 presents the variation in power of the three best paths 1606, 1608 and 1610 at different distances; with the Y-Axis 1602 representing amplitude and the X-Axis 1604 representing range. Also shown is the coherent sum of the ten largest correlations 1612 as might be obtained with a variable tap rake receiver. The "+" sign indicates the coherent sum of the top ten correlation values as might be obtained from a variable tap rake receiver.

FIG. 17 shows the time of arrival of the three best correlations (time relative to scan start time) in a variable position testing environment. The Y-Axis 1702 represents the Time of Arrival and the X-Axis 1704 represents the Location Number. The location number corresponds to a different testing position throughout a testing environment. The largest (i.e. best or strongest) correlation is marked with "O" 1706, the second largest with "+' 1708, and the third largest with "*" 1704. From this figure it can be seen that sometimes the strongest correlation is not the earliest arriving signal, e.g., at the third location, the strongest correlation occurred three nanoseconds after the third best correlation. By providing a scanning correlator in addition to a tracking correlator, the best correlation times can be ascertained.

As mentioned above, the multiple correlator receiver can have great flexibility with respect to the number of timing generators and correlators in a given receiver. This determination will be based on design factors. FIG. 18 is an overview block diagram illustrating eight correlators – one of the correlators may be used as a pulser as illustrated in FIG. 19. In this design there are eight channels with one transmit channel, one scan channel and six receive channels. Impulse radio signals will be received by antenna 1802 and passed to power splitter 1804 whereafter RF Signals are passed to the plurality of correlators 1812, 1810, 1808, 1806 (in this case seven). Correlators 1A and 1B are at 1812 and provide transmitting and scanning functionality, Correlators 2A and 2B are at 1810 and provide 2 receive channels, Correlators 3A and 3B are at 1808 and provide two additional receive channels, Correlators 4A and 4B are at 1806 and provide another two receive channels.

The output of each correlator passes to baseband 1, 1814 or baseband 2, 1816, which can be connected via a cascade port (or any other interface between basebands to pass signal information). The output of the basebands, 1814 and 1816, are then sent to the processor 1818.

FIG. 19 more particularly sets forth the correlator configuration within a digital impulse radio architecture. Dashed line 1904 illustrates the components that would be included in blocks 1812, 1810, 1808 and 1806 of FIG. 18. Oscillator 1948 drives the master timer 1930 which triggers correlator 1902 and controls timer 1932 that triggers correlator 1922. It also triggers timer 1934 which triggers correlator 1924; triggers timer 1936 that triggers correlator 1926; and triggers timer 1938 which triggers pulser 1928.

Bus control 1950 controls address 1974 and data 1976 information between the timers 1930 – 1938, the processor 1952 and baseband 1954. The master timer also controls the system timing of the baseband 1954. The functionality included in the baseband is acquisition 1956 (both detection 1958 and verification 1960), data modulation and demodulation 1972, tracking 1964, link monitoring 1966 and analog to digital conversion 1968. A data source/link 1962 is interfaced with data modulation and demodulation 1972. The correlators

1902, 1922, 1924 and 1926 can go through a sample and hold process prior to communication with baseband 1954 via ADC 1968. The link monitor monitors the signal to noise ratio and/or the bit error rate to determine signal quality. If the bit error rate or signal to noise ratio fall below a preset criteria another acquisition and lock will be required. The signals received by the correlators originated from antenna 1946 which then pass through the transmit/receive switch 1944, which is in receive mode, through a low noise amplifier/filter 1942, a variable attenuator 1940 and finally through amplifiers 1906, 1908, 1910, and 1920, with each connected with respective correlators.

If the radio is in transmit mode, the timers 1930 - 1938 connect directly with pulser 1928 which emits pulses through antenna 1946 via transmit/receive switch 1944.

FIG. 20 illustrates the flexibility of the design wherein a distinct timer configuration is used. In this case, a separate timer is not associated with a given correlator, but rather timing master 2002 triggers correlator 2004 and, after delay 2008, also triggers correlator 2006. Thus, in essence correlator 2006 can be a slave of correlator 2004. Another timer 2012, driven by master timer 2002, triggers correlator 2010 and also, again after another delay 2016, triggers correlator 2014. A last timer 2018 can drive the pulser 2020 if the transceiver is acting as a transmitter. The remainder of the diagram is similar to FIG. 19, as addressed by the following description.

When transmit/receive switch 2024 is in receive mode, impulse radio antenna 2022 receives RF pulses, whereafter they pass to low noise amplifier/filter 2026. After passing through variable attenuator 2028, the RF signal passes through amplifiers 2030-2036 and into correlators 2004, 2006, 2010 and 2014. The correlator trigger timing is according to the aforementioned with correlator 2006 being a slave according to delay 2008 of correlator 2004 and correlator 2014 being a slave according to delay 2016 of correlator 2010. Again, the above configuration is for illustration only as any number of configurations are anticipated.

After correlation has occurred in each respective correlator, the correlated analog signal goes through an optional sample and hold and passes to analog to digital converter 2058 located in baseband 2044. As with the impulse radio of FIG. 19, the baseband provides link monitoring 2056, tracking 2054 and data modulation and demodulation 2064. The baseband also takes care of the acquisition 2046 functions of detection 2048 and verification 2050. A data source/link 2052 is also connected to baseband 2052.

Again, as with the multiple correlator impulse radio architecture of FIG. 19, bus control 1040 controls address and data information to and from the master timer 2002, timer 2012, timer 2018, processor 2042 and baseband 2044. The timing for the baseband is provided by master timer 2002 as depicted at 2066, which is driven by oscillator 2038.

If the impulse radio is in transmit mode then the oscillator 2038 drives the master timer 2002 which drives timer 2018 which triggers the pulser 2020, which transmits RF pulses to antenna 2022 via transmit/receive switch 2024.

FIG. 21 is yet another distinct configuration of a multiple correlator receiver wherein slaved correlators are utilized and driven by the same timer as the master correlator with a delay therebetween. Herein master timer 2002 triggers correlator 2004. Correlator 2008 is slaved to correlator 2004 via delay 2006. Further, correlator 2012 is slaved to correlator 2004 via delay 2010. Correlator 2014 is triggered by slave timer 2016 which is driven by master timer 2002. Correlator 2020 is triggered by and slaved to via delay 2018, correlator 2014. The remainder of the diagram remains as in FIG. 19 and FIG. 20. As demonstrated, the number of correlators, whether or not they are slaved to preceding or subsequent correlators, the number of timers and whether they are slaved are all design options built according to the parameters dictated and the results desired.

While particular embodiments of the invention have been described, it will be understood, however, that the invention is not limited thereto, since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings. It is, therefore, contemplated by the appended claims to

cover any such modifications that incorporate those features or those improvements which embody the spirit and scope of the present invention.

What Is Claimed Is:

1. An impulse radio receiver, comprising:

a time base that provides a timing signal;

a plurality of timing generators that use said timing signal to produce a timing trigger signal;

at least one template generator corresponding to said plurality of said timing generators that uses said timing trigger signal to produce a template signal; and

at least one correlator triggered by said plurality of said timing generators that correlates a received impulse radio signal with said template signal to produce a correlator output signal.

2. An impulse radio receiver, comprising:

a time base that provides a timing signal;

a plurality of timing generators that use said timing signal to produce a timing trigger signal;

a plurality of template generator corresponding to said plurality of said timing generators that uses said timing trigger signal to produce a template signal; and

a plurality of correlators triggered by said plurality of said timing generators that correlates a received impulse radio signal with said template signal to produce a correlator output signal.

3. The impulse radio receiver of claim 2, wherein said plurality of timing generators includes at least one master timing generator and at least one slave timing generator associated with said master timing generator.

4. The impulse radio receiver of claim 3, wherein said at least one master timing generator triggers at least one correlator and said at least one slave timing generator triggers at least one additional correlator.

5. The impulse radio receiver of claim 2, wherein one of said plurality of timers triggers one of said plurality or said correlators and wherein at least a second of said plurality of said correlators is triggered by the same timer via a delay.

6. The impulse radio receiver of claim 5, wherein said delay is successively increased.

7. The impulse radio receiver of claim 2, further comprising an ultra-wide band antenna for receiving wide band RF pulses.

8. The impulse radio receiver of claim 7, further comprising a low noise amplifier in communication with said antenna.

9. The impulse radio receiver of claim 6, further comprising a variable attenuator acting on said RF pulses prior to correlation.

10. The impulse radio receiver of claim 6, further comprising at least one amplifier in communication with said plurality of said correlators acting on said RF pulses prior to correlation.

11. The impulse radio receiver of claim 2, further comprising a baseband signal processor operatively connected to said plurality of timers.

12. The impulse radio receiver of claim 2, further comprising a control bus that communicates address and data information within said impulse radio receiver.

13. The impulse radio receiver of claim 2, further comprising an acquisition means in communication with said plurality of timers and said baseband processor via said control bus.

14. The impulse radio receiver of claim 2, further comprising a link monitoring means in communication with said plurality of timers and said baseband processor via said control bus.

15. The impulse radio receiver of claim 2, further comprising an analog to digital converter for receiving analog signals from said plurality of correlators and converting said analog signals to digital signals, wherein said and is in communication with said plurality of timers and said baseband processor via said control bus.

16. The impulse radio receiver of claim 2, further comprising a data source in communication with said data modulation and demodulation means.

17. A method of RF impulse waveform propagation analysis, comprising the steps of:

receiving an impulse radio RF signal;

locking on and tracking at a tracking point said received impulse radio RF signals utilizing at least one tracking correlator; and

scanning and sampling the received waveform at precise time delays relative to said tracking point utilizing at least one scanning correlator.

18. The method of RF impulse waveform propagation analysis of claim 17, wherein said step of scanning and sampling the received waveform at precise time delays relative to said tracking point utilizing at least one scanning correlator, utilizes a plurality of scanning correlators each at distinct time delays relative to said tracking point.

19. The method of RF impulse waveform propagation analysis of claim 17, wherein said step of successively increasing said time delay while sampling said waveform.

20. The method of RF impulse waveform propagation analysis of claim 17, wherein said step of scanning and sampling the received waveform at precise time delays relative to said tracking point utilizing at least one scanning receiver, utilizes a plurality of scanning receivers each at distinct time delays relative to a corresponding canning correlator.

21. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of amplifying said RF signal prior to correlation by at least one of said tracking correlators.

22. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of amplifying said RF signal prior to correlation by said at least one of said scanning correlators.

23. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of amplifying said RF signal prior to correlation by said scanning and tracking correlator.

24. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of controlling the address and data information between a plurality of timers, a baseband processor, an acquisition means, a data modulation and demodulation means, a tracking means and a link monitoring means with a control bus.

25. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of acquiring a signal with an acquisition means.

26. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of modulating and demodulating data with a data modulating and data demodulating means.

27. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of monitoring a link with link monitoring means.

28. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of attenuating said RF pulses prior to correlation by at least one of said scanning or tracking correlators by a variable attenuator.

29. The method of RF impulse waveform propagation analysis of claim 17, further comprising the step of filtering and low noise amplifying said RF pulses prior to correlation by at least one of said scanning or tracking correlators.

30. An apparatus for RF impulse waveform propagation analysis, comprising:

a means for providing a timing signal;

a plurality of timing generator means that use said timing signal to produce a timing trigger signal;

a plurality of template generator means corresponding to said plurality of said means for providing a timing signal that uses said timing trigger signal to produce a template signal; and

a plurality of pulse correlation means triggered by said plurality of said timing generator means that correlates a received impulse radio signal with said template signal to produce a correlator output signal.

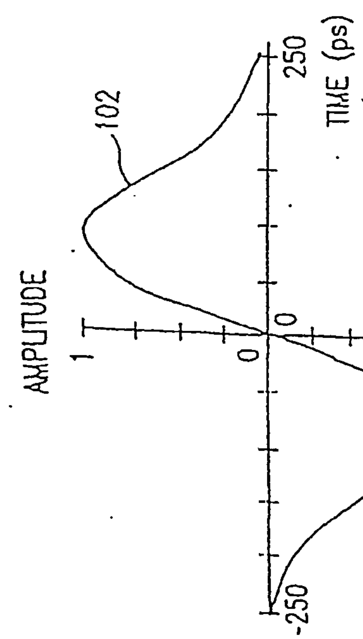

AMPLITUDE
1
0
-1
102
-250
0
250
TIME (ps)

FIG.1A

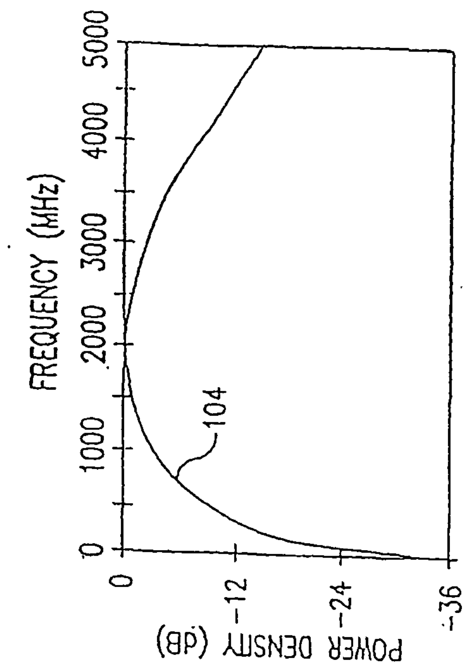
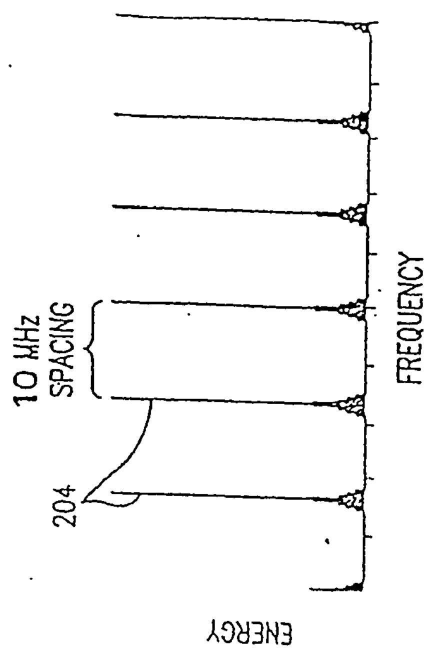
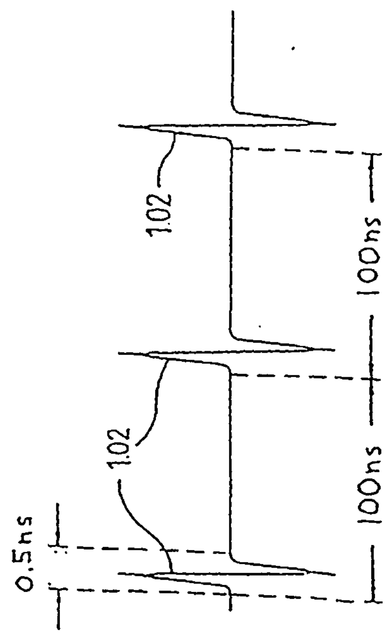

FREQUENCY (MHz)
0
1000
2000
3000
4000
5000
104
0
−12
−24
-36
POWER DENSITY (dB)

FIG.1B


10 MHz SPACING
204
FREQUENCY
ENERGY
FIG.2B


0.5ns
1.02
1.02
100ns
100ns
FIG.2A

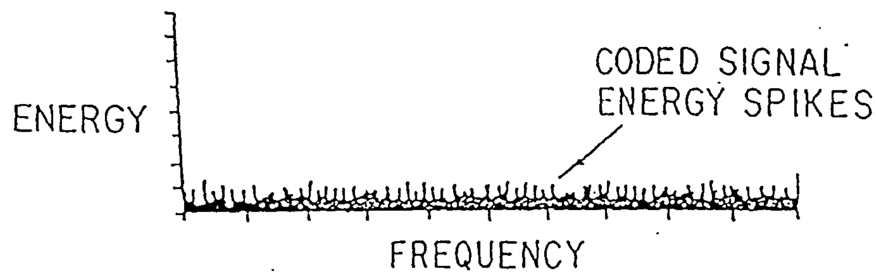


FIG. 3

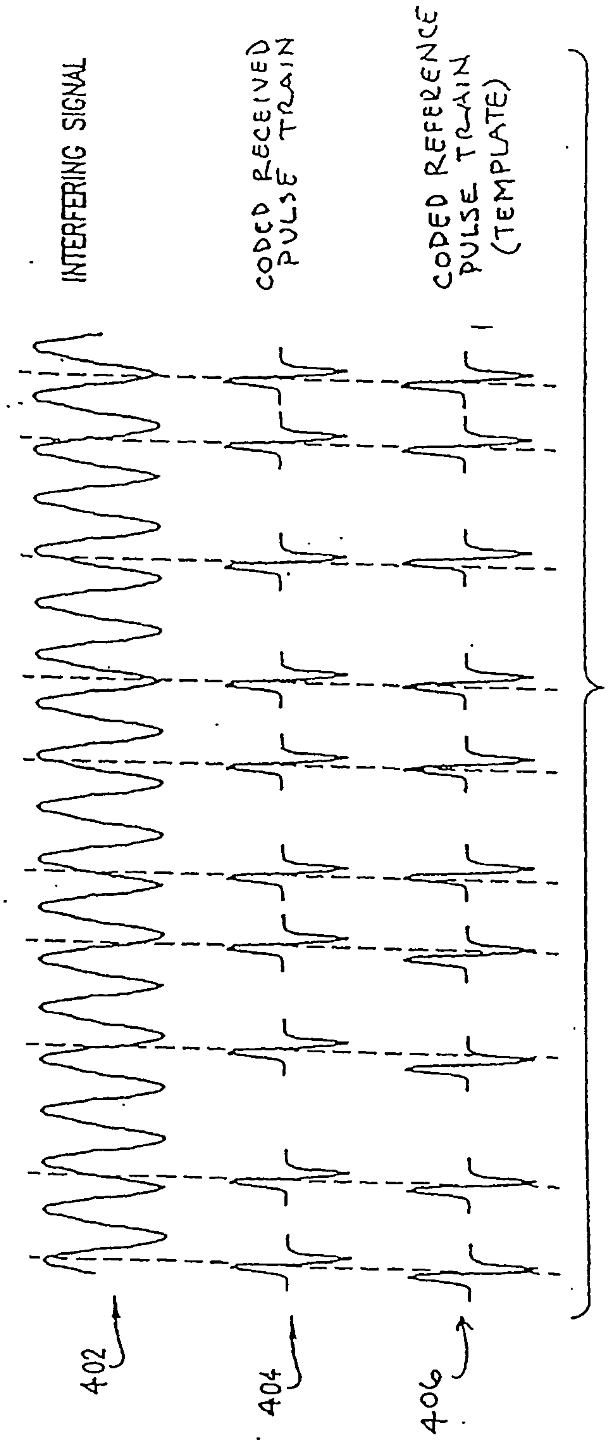

INTERFERING SIGNAL
CODED RECEIVED PULSE TRAIN
CODED REFERENCE PULSE TRAIN (TEMPLATE)
402
404
406

FIG. 4

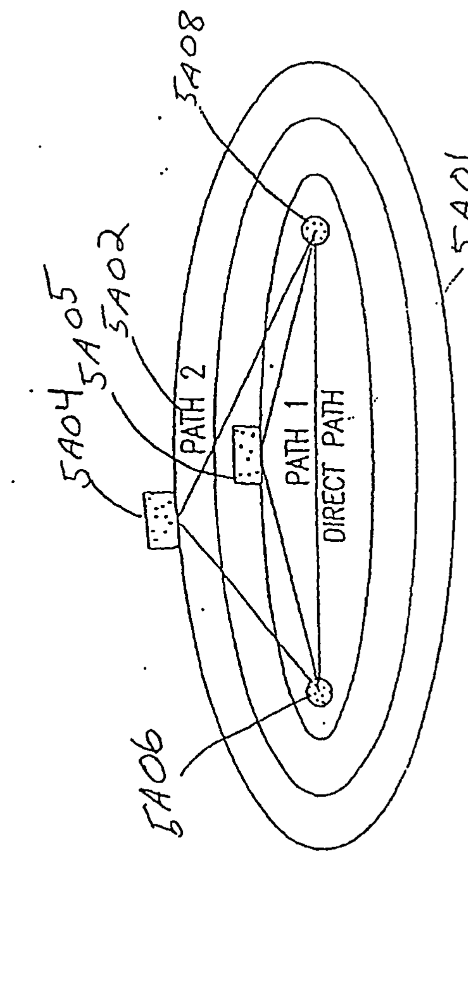

5A04
5A05
5A02
5A08
5A06
5A01
PATH 2
PATH 1
DIRECT PATH

FIG.5A

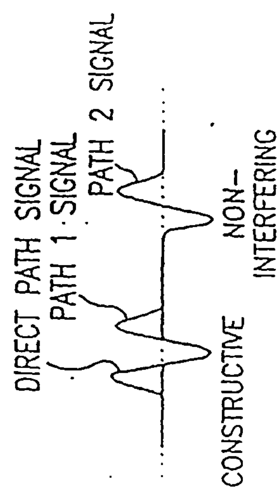

DIRECT PATH SIGNAL
PATH 1 SIGNAL
PATH 2 SIGNAL
CONSTRUCTIVE
NON-INTERFERING

FIG.5B

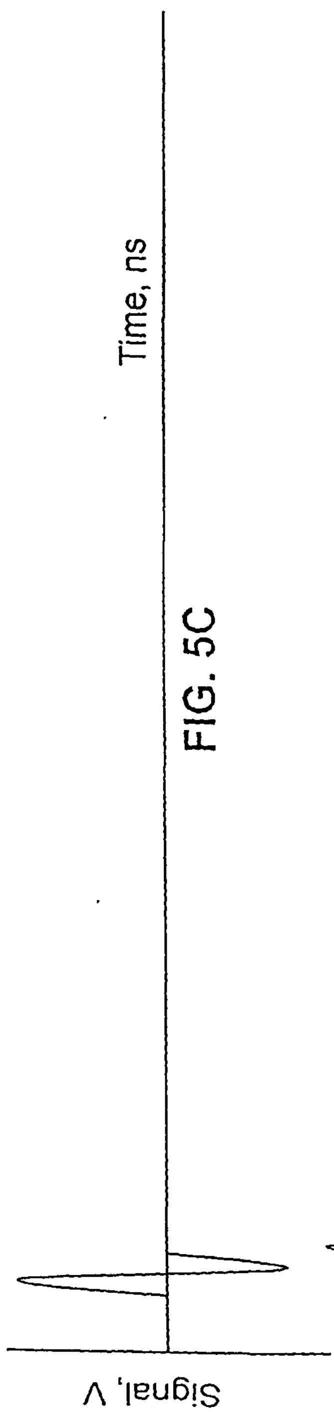


FIG. 5C

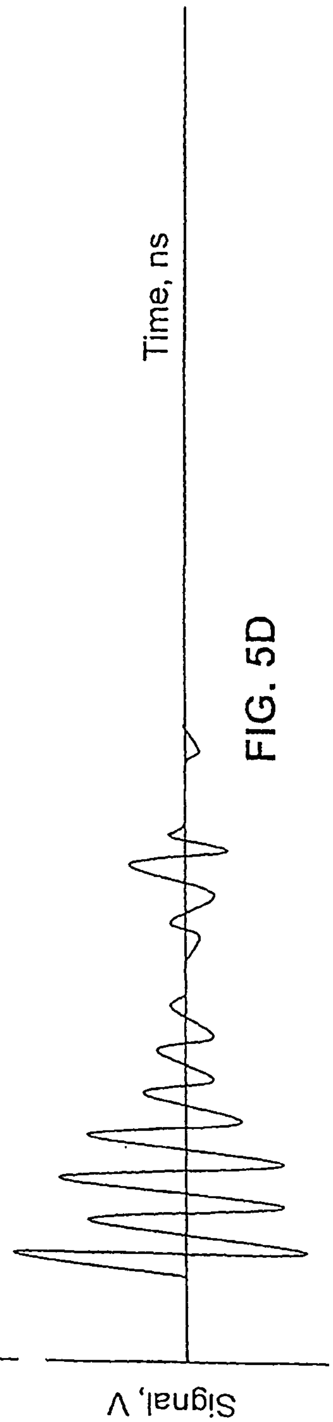


FIG. 5D

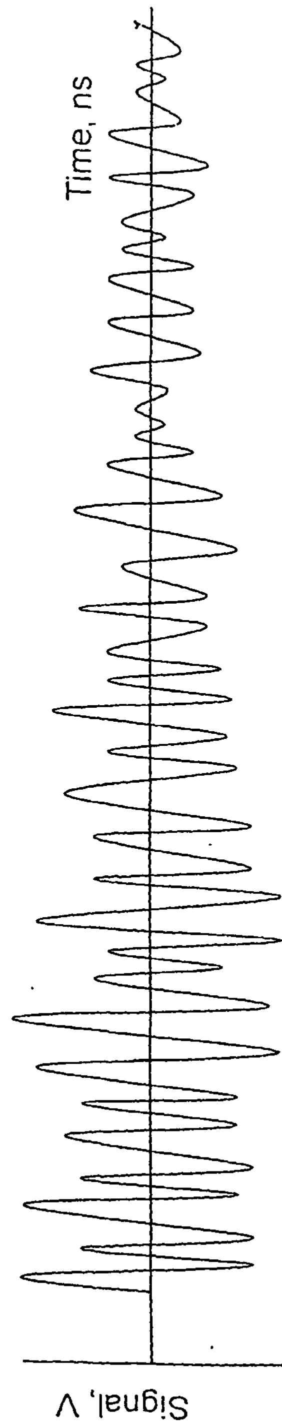


FIG. 5E

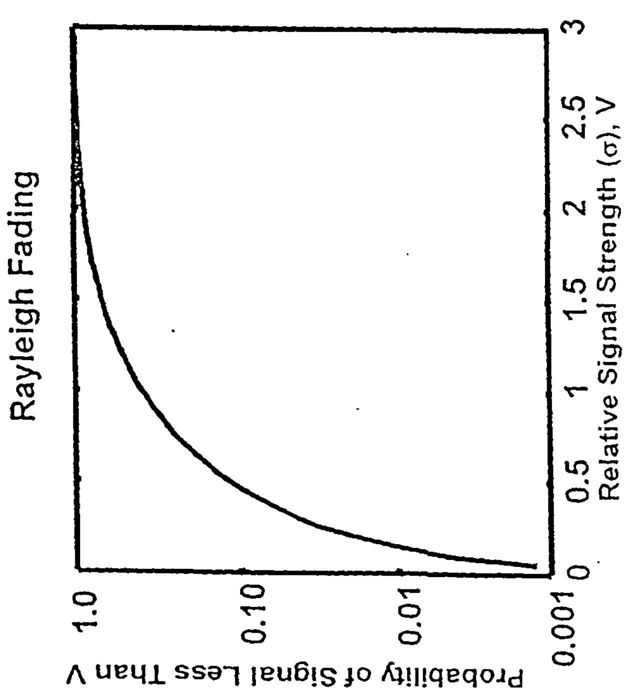

Rayleigh Fading
Probability of Signal Less Than V
1.0
0.10
0.01
0.001
0
0.5
1
1.5
2
2.5
3
Relative Signal Strength (σ), V

Fig. 5F

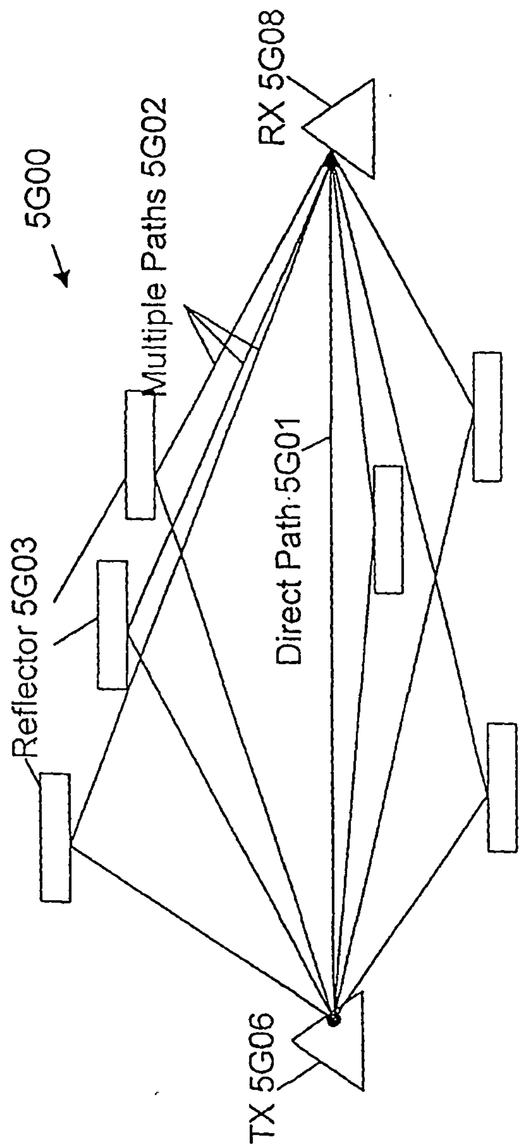

5G00
Multiple Paths 5G02
RX 5G08
Reflector 5G03
Direct Path 5G01
TX 5G06

FIG. 5G

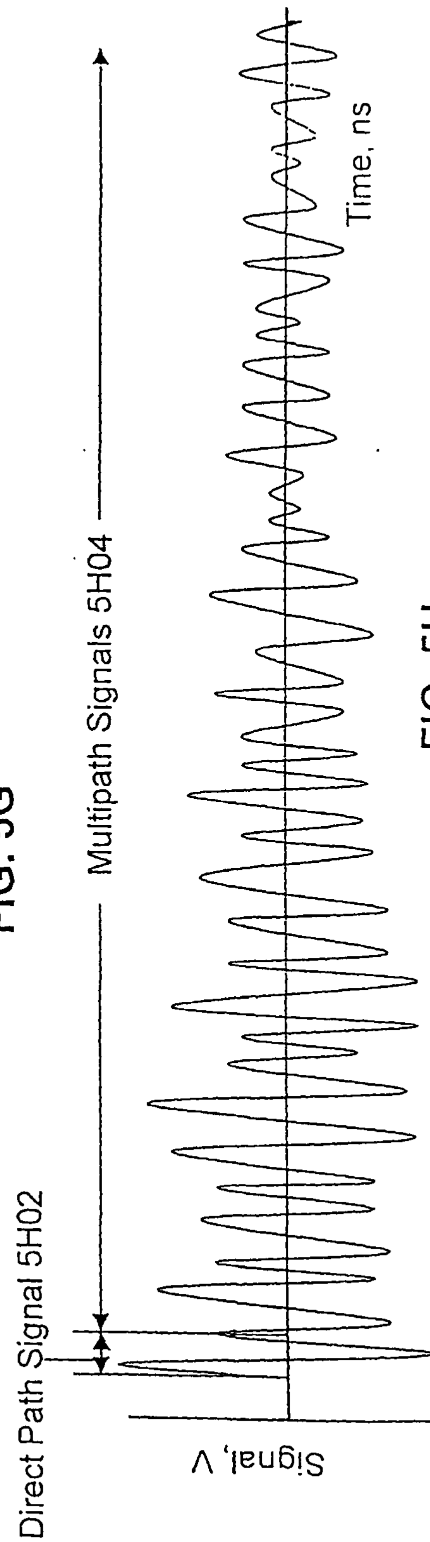

Multipath Signals 5H04
Time, ns
Direct Path Signal 5H02
Signal, V

FIG. 5H

FIG. 7

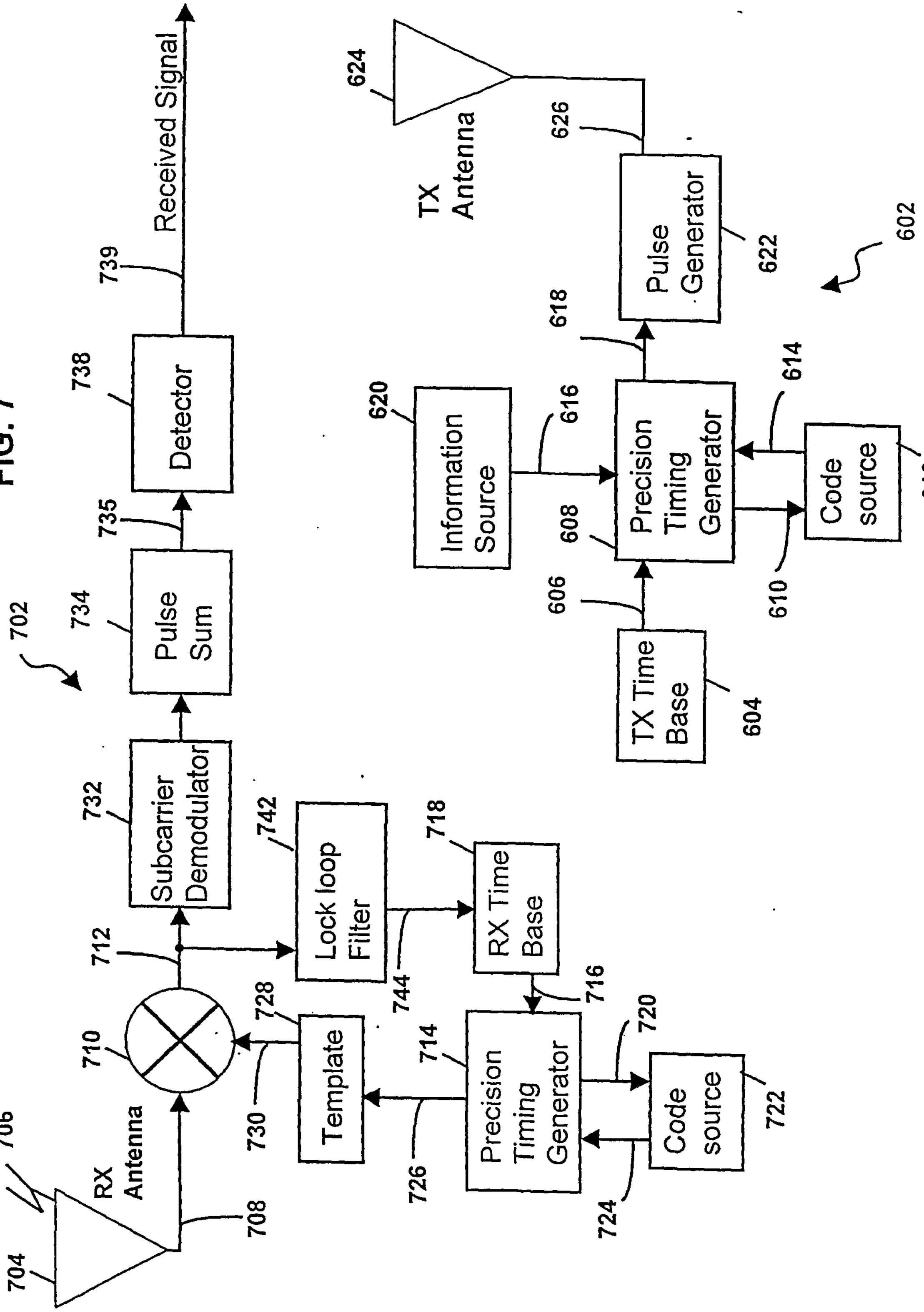

702
704
706
RX Antenna
708
710
712
Subcarrier Demodulator
732
Pulse Sum
734
735
Detector
738
739
Received Signal
Lock loop Filter
742
744
RX Time Base
718
716
Template
728
730
Precision Timing Generator
714
726
Code source
720
722
724
602
TX Time Base
604
606
Precision Timing Generator
608
Information Source
620
616
Code source
610
612
614
618
Pulse Generator
622
626
TX Antenna
624

FIG. 6

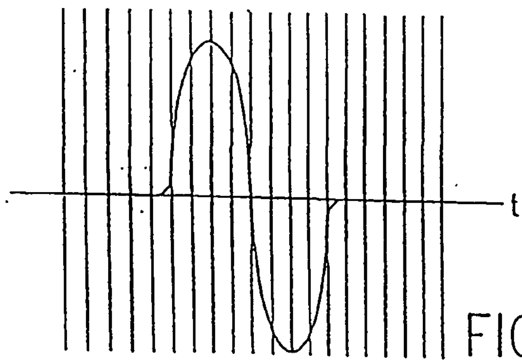


FIG. 8A

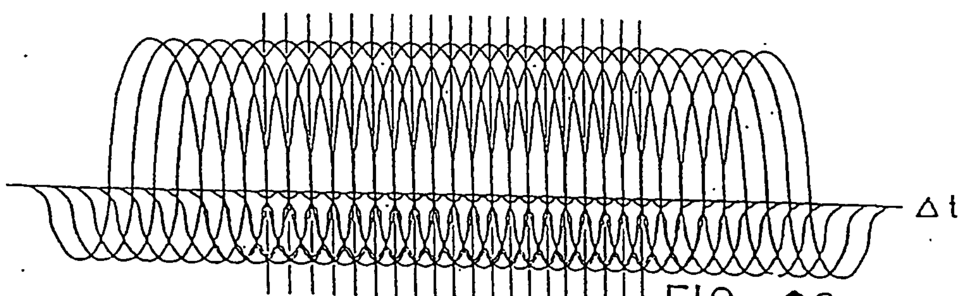


FIG. 8B

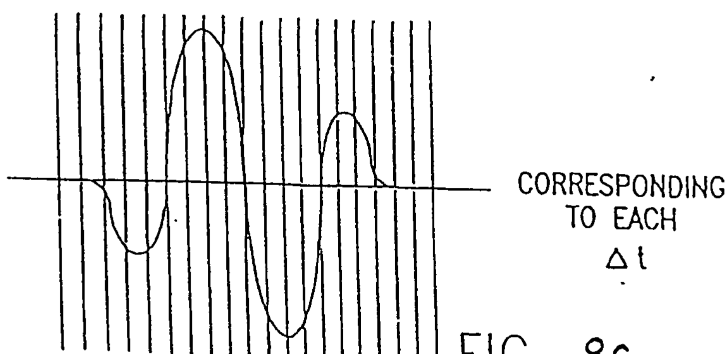
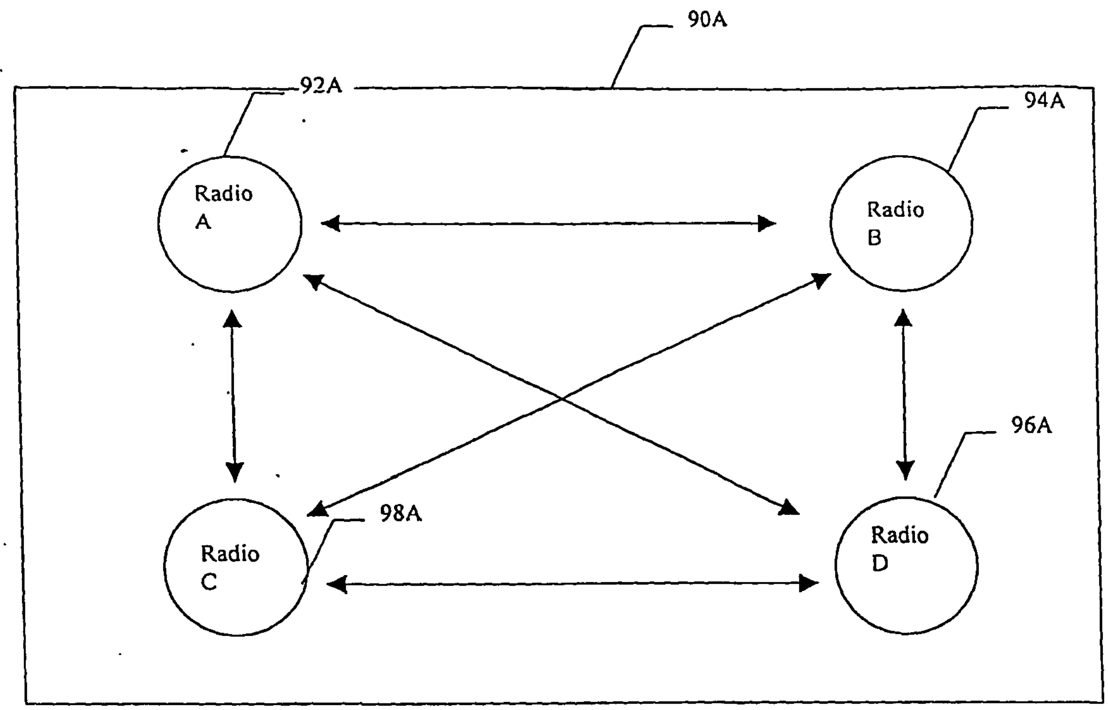


FIG. 8C



Four nodes in an Impulse Radio TDMA linked network

FIG. 9A

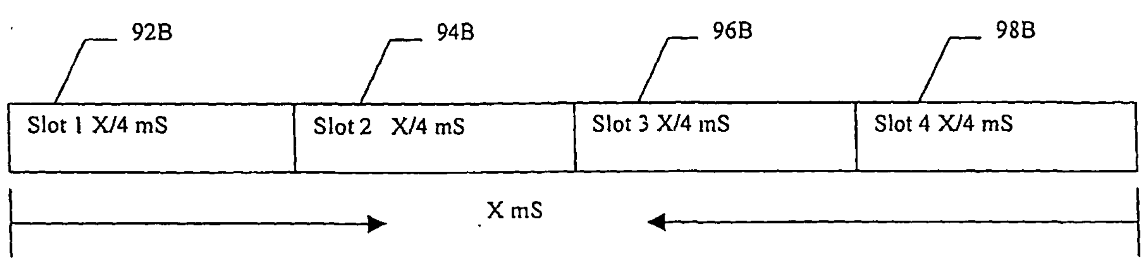


FIG. 9B

FIG. 10

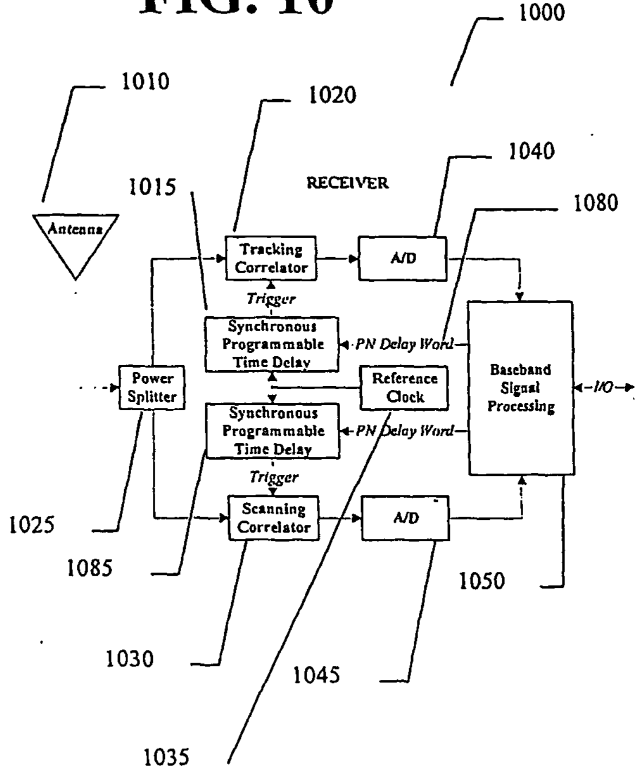

1000
1010
1020
1040
1015
RECEIVER
1080
Antenna
Tracking Correlator
A/D
Trigger
Synchronous Programmable Time Delay
PN Delay Word
Power Splitter
Reference Clock
Baseband Signal Processing
I/O
Synchronous Programmable Time Delay
PN Delay Word
Trigger
Scanning Correlator
A/D
1025
1085
1050
1030
1045
1035

FIG. 11

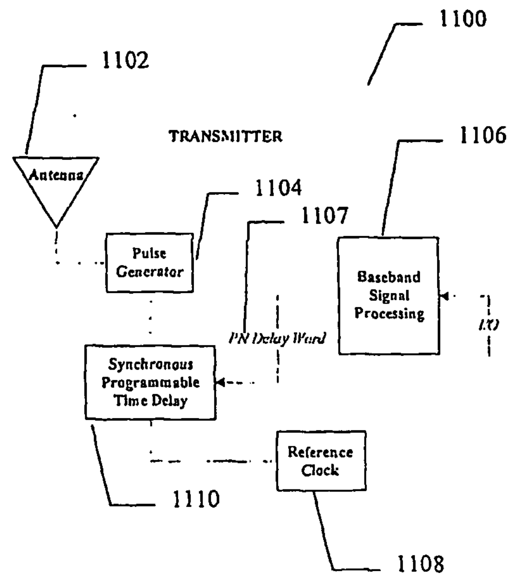

1100
1102
TRANSMITTER
1106
Antenna
1104
1107
Pulse Generator
Baseband Signal Processing
PN Delay Word
I/O
Synchronous Programmable Time Delay
Reference Clock
1110
1108

FIG. 12

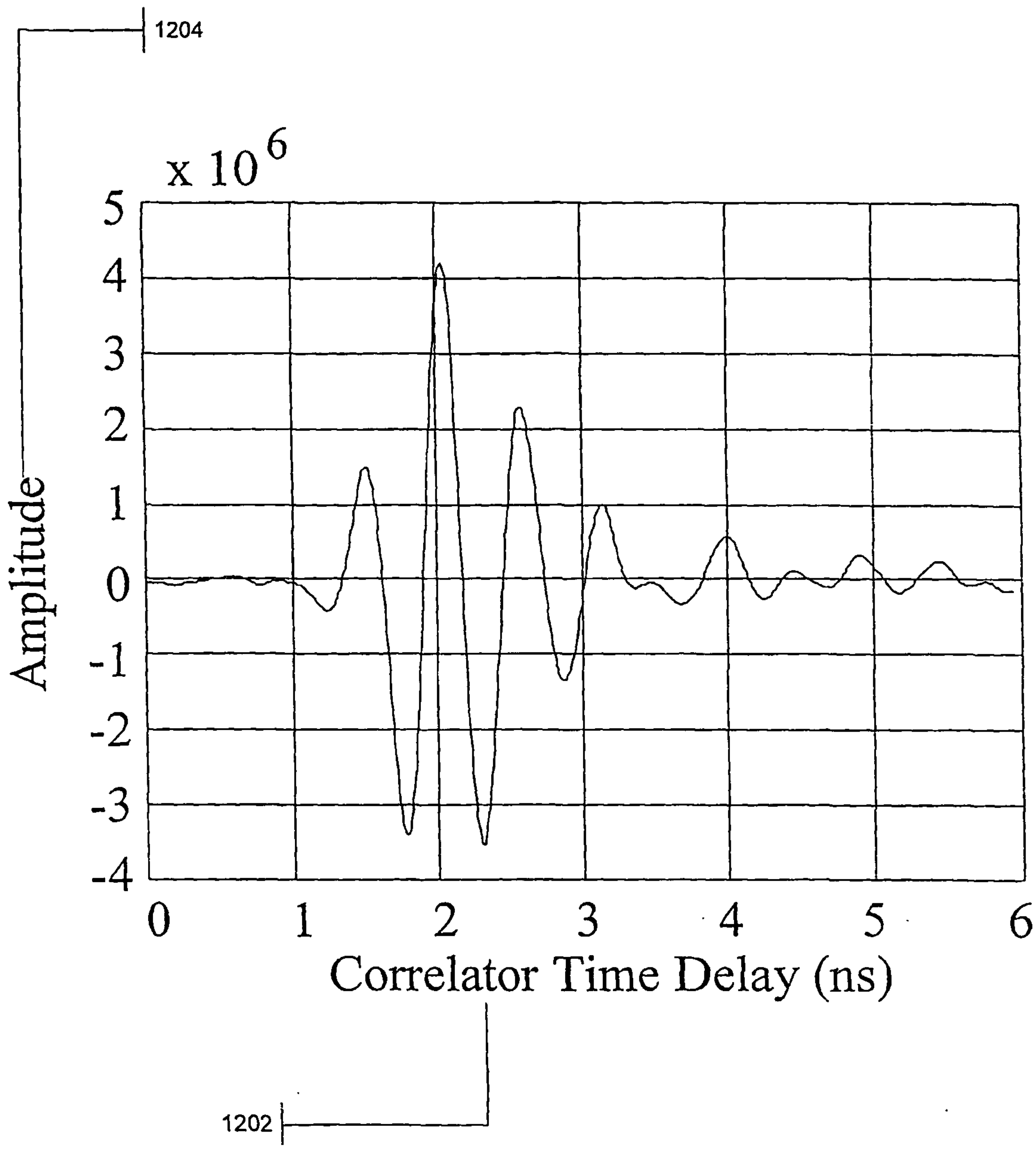
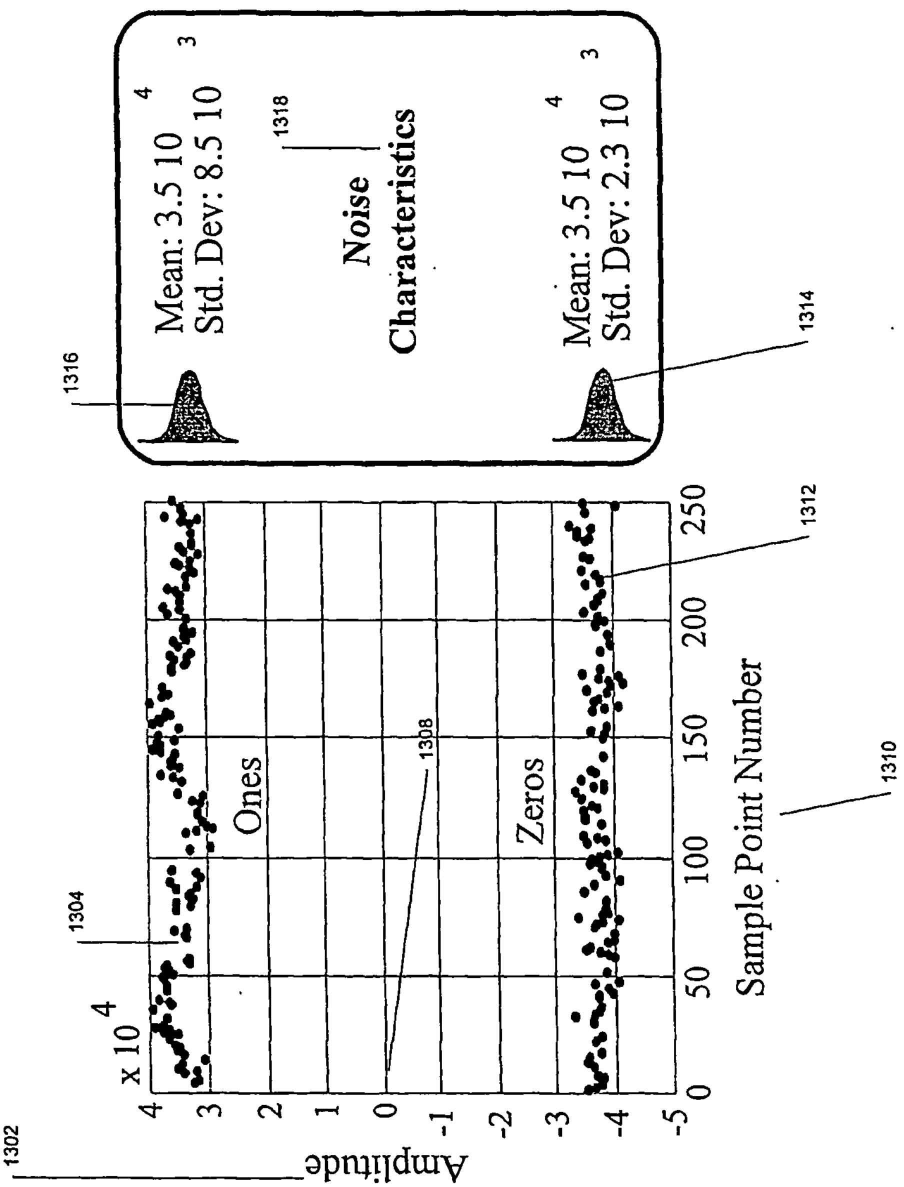

1204
x 10^6
5
4
3
2
1
0
-1
-2
-3
-4
Amplitude
0
1
2
3
4
5
6
Correlator Time Delay (ns)
1202

FIG. 13



Mean: 3.5 10 4
Std. Dev: 8.5 10 3
Noise
Characteristics
Mean: 3.5 10 4
Std. Dev: 2.3 10 3
1316
1318
1314
x 10 4
Ones
Zeros
Amplitude
Sample Point Number
1302
1304
1308
1310
1312

FIG. 14

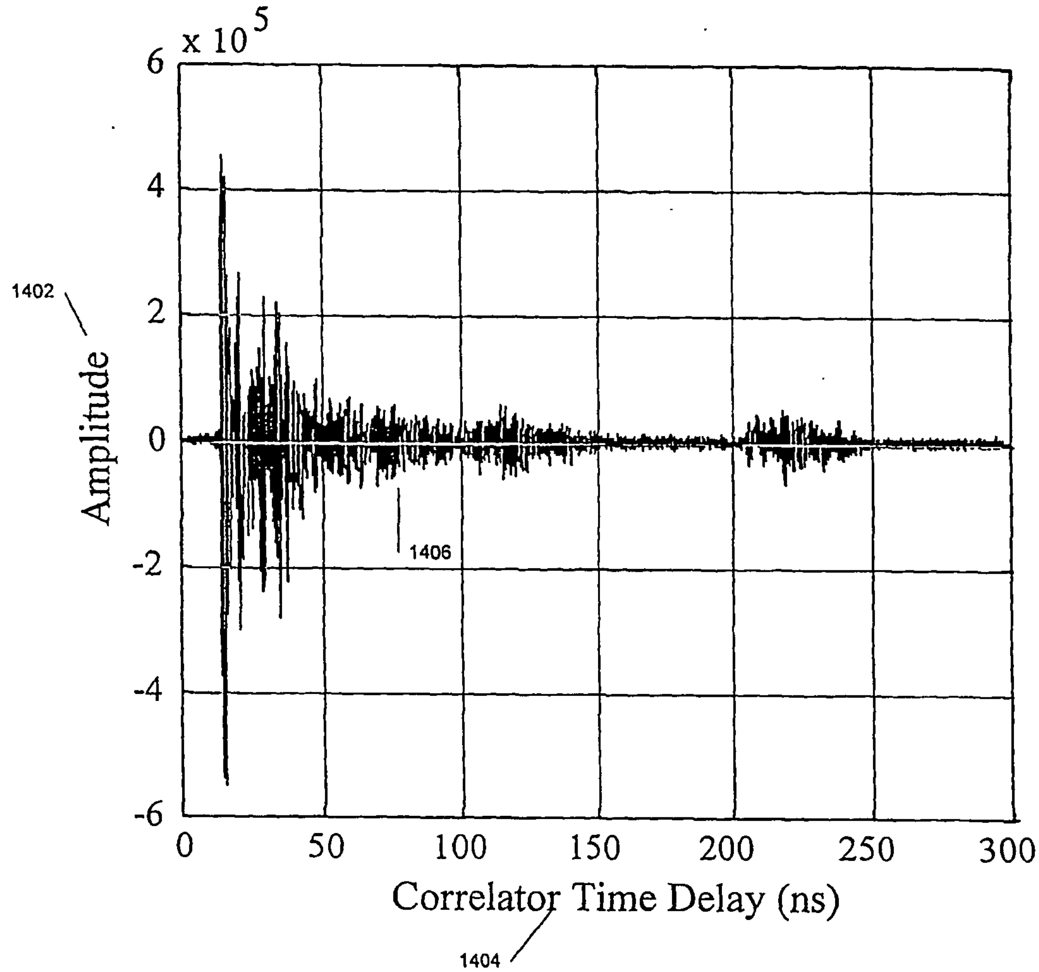

x 10^5
6
4
2
0
-2
-4
-6
Amplitude
1402
1406
0
50
100
150
200
250
300
Correlator Time Delay (ns)
1404

FIG. 15

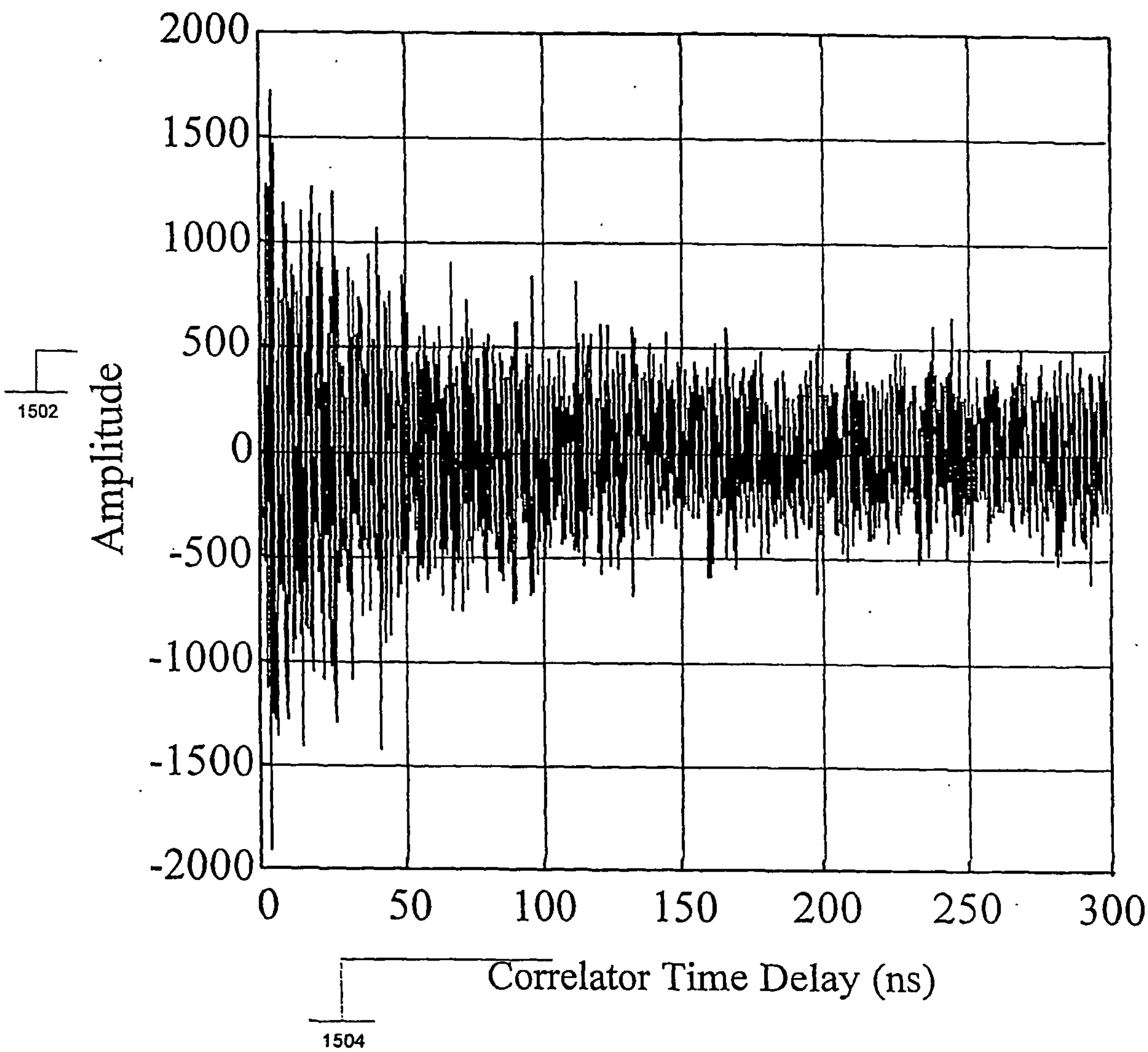

2000
1500
1000
500
0
-500
-1000
-1500
-2000
Amplitude
1502
0
50
100
150
200
250
300
Correlator Time Delay (ns)
1504

FIG. 16

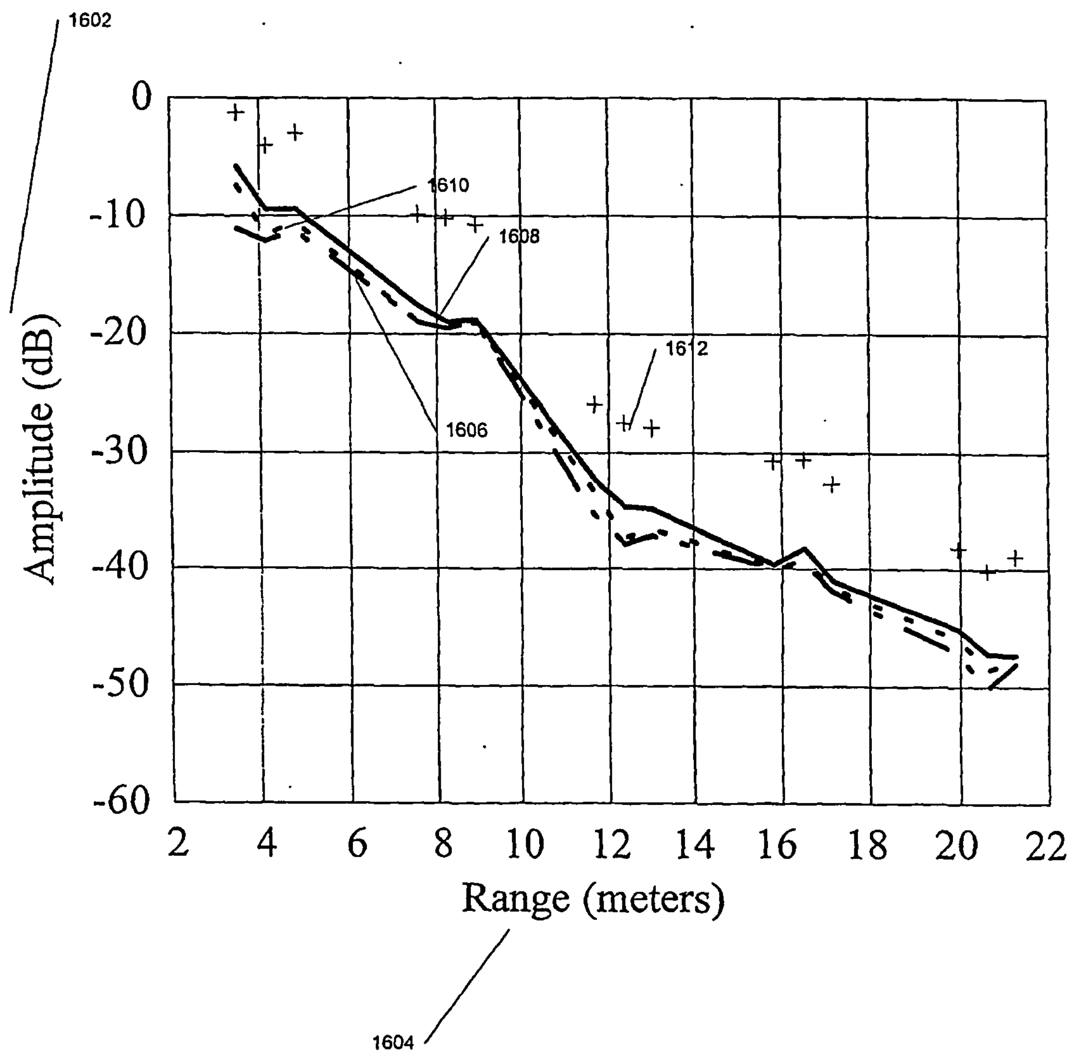
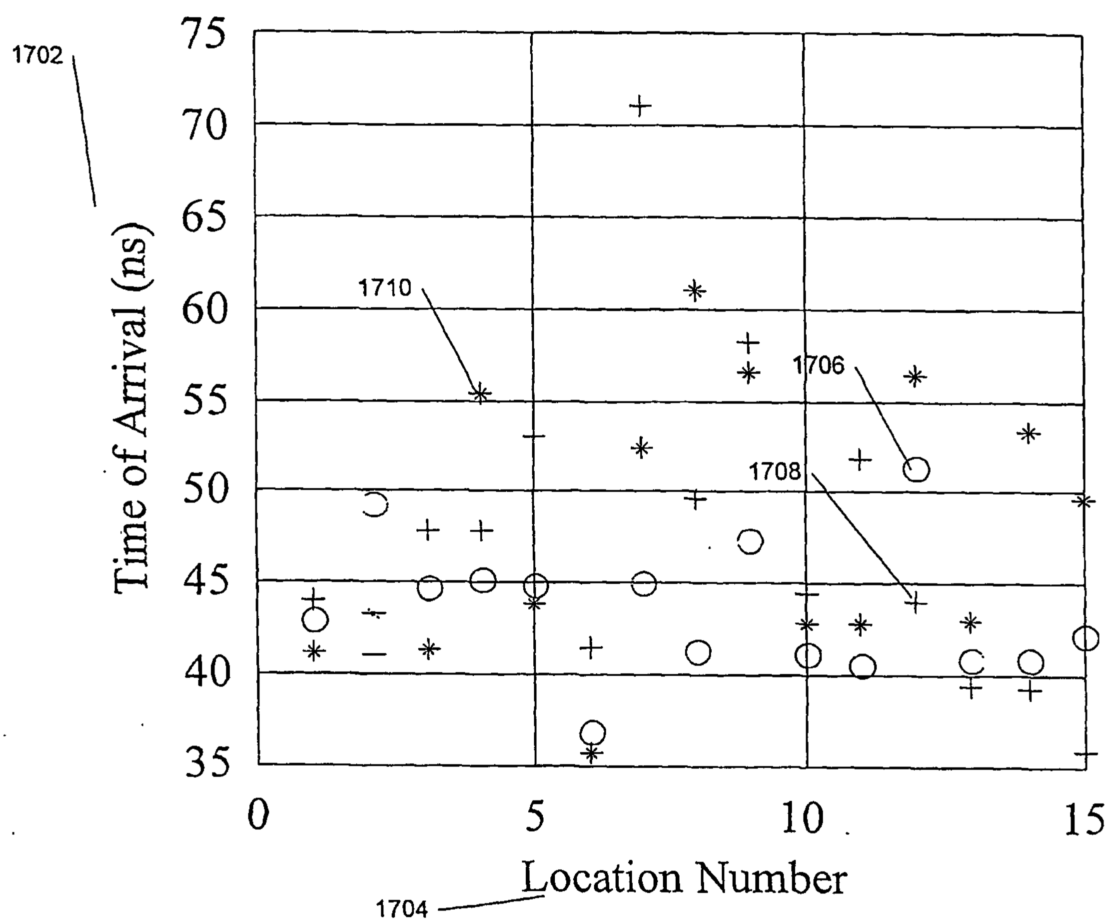

1602
0
-10
-20
-30
-40
-50
-60
Amplitude (dB)
1610
1608
1612
1606
2
4
6
8
10
12
14
16
18
20
22
Range (meters)
1604

FIG. 17


1702
75
70
65
60
55
50
45
40
35
Time of Arrival (ns)
1710
1706
1708
0
5
10
15
Location Number
1704

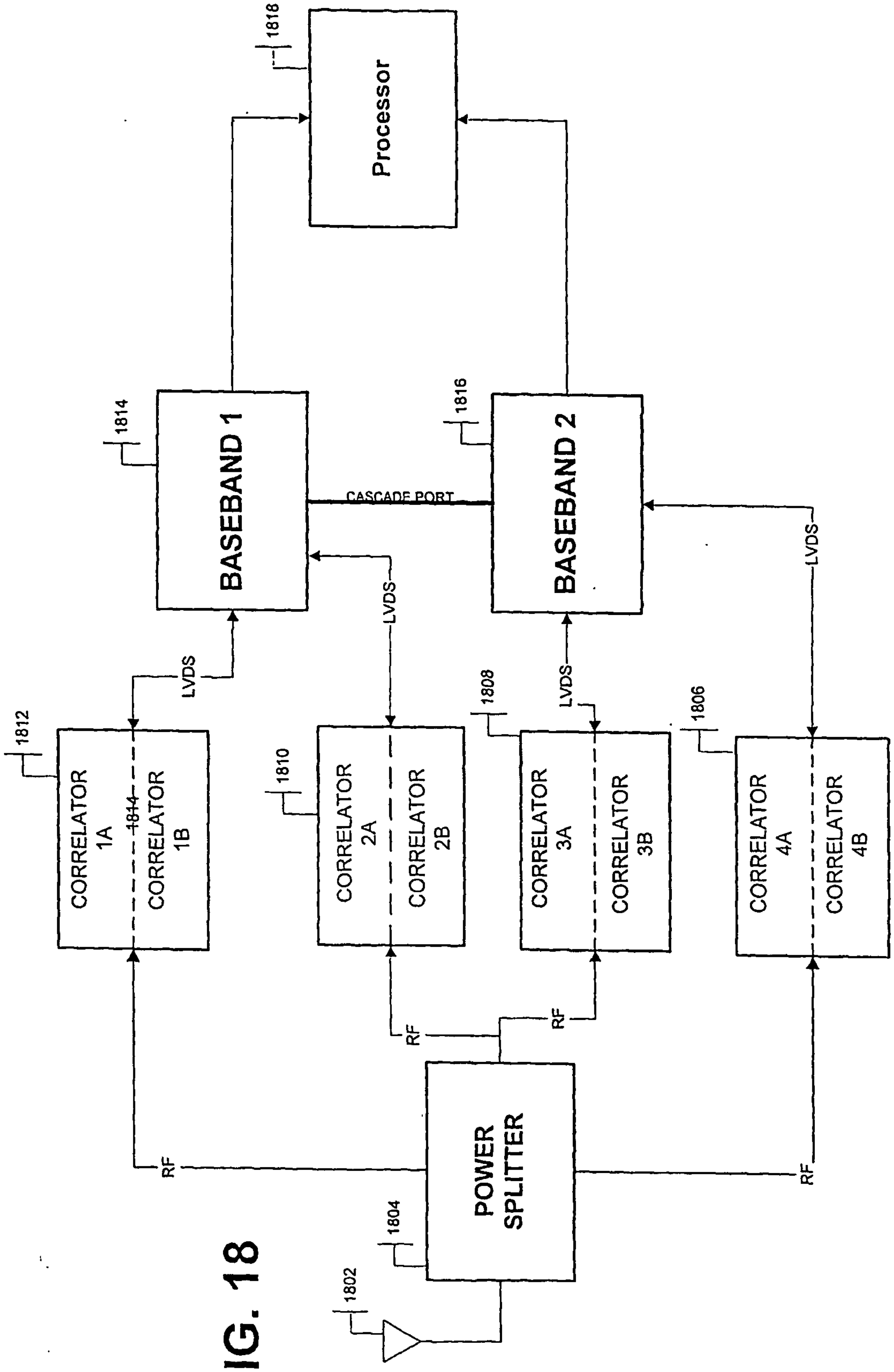

Processor
1818
BASEBAND 1
1814
CASCADE PORT
BASEBAND 2
1816
LVDS
LVDS
LVDS
LVDS
CORRELATOR 1A
1814
CORRELATOR 1B
1812
CORRELATOR 2A
CORRELATOR 2B
1810
CORRELATOR 3A
CORRELATOR 3B
1808
CORRELATOR 4A
CORRELATOR 4B
1806
RF
RF
RF
RF
POWER SPLITTER
1804
1802

FIG. 18

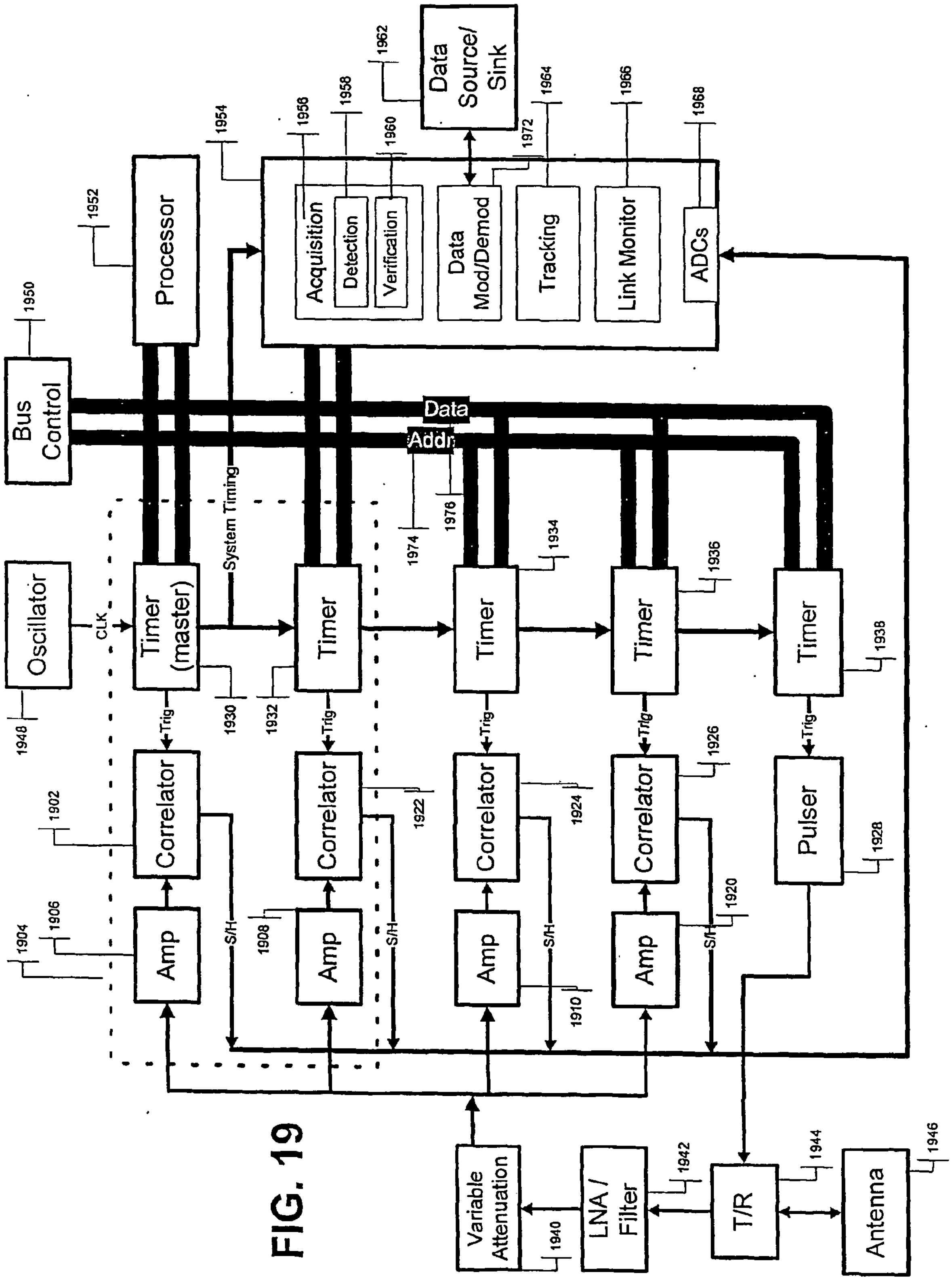

Data Source/ Sink
1962
Processor
1952
1954
1956
1958
1960
1972
1964
1966
1968
Acquisition
Detection
Verification
Data Mod/Demod
Tracking
Link Monitor
ADCs
Bus Control
1950
Data
Addr
Oscillator
1948
CLK
Timer (master)
System Timing
Timer
Timer
Timer
Timer
1974
1976
1930
1932
1934
1936
1938
Trig
Correlator
Correlator
Correlator
Correlator
Pulser
1902
1922
1924
1926
1928
Amp
Amp
Amp
Amp
1904
1906
1908
1910
1920
S/H
Variable Attenuation
LNA / Filter
T/R
Antenna
1940
1942
1944
1946

FIG. 19

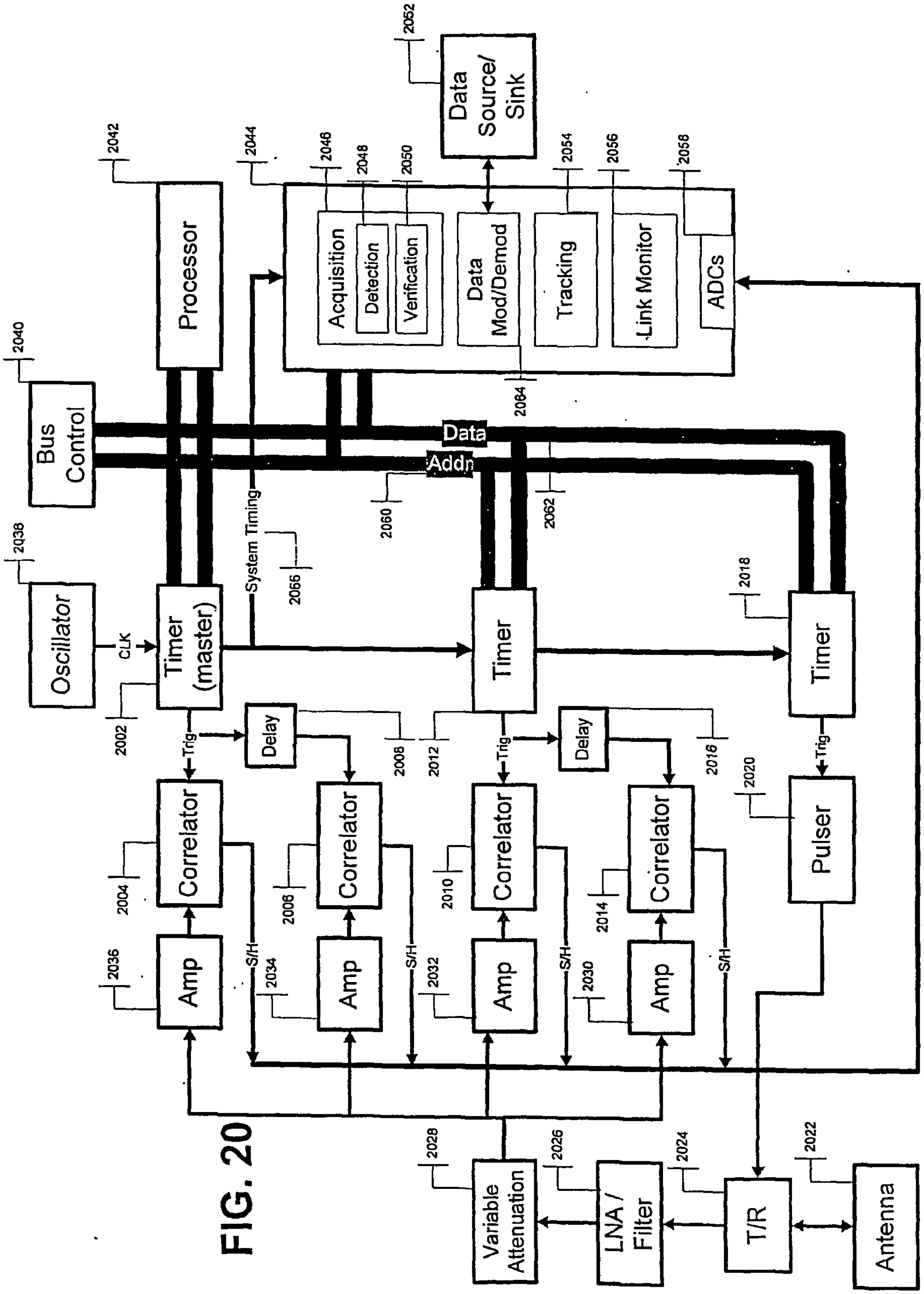

Oscillator
CLK
Timer (master)
Bus Control
Processor
System Timing
Acquisition
Detection
Verification
Data Mod/Demod
Tracking
Link Monitor
ADCs
Data Source/ Sink
Data
Addr
Timer
Timer
Trig
Delay
Trig
Delay
Trig
Correlator
Correlator
Correlator
Correlator
Pulser
S/H
S/H
S/H
S/H
Amp
Amp
Amp
Amp
Variable Attenuation
LNA / Filter
T/R
Antenna
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066

FIG. 20

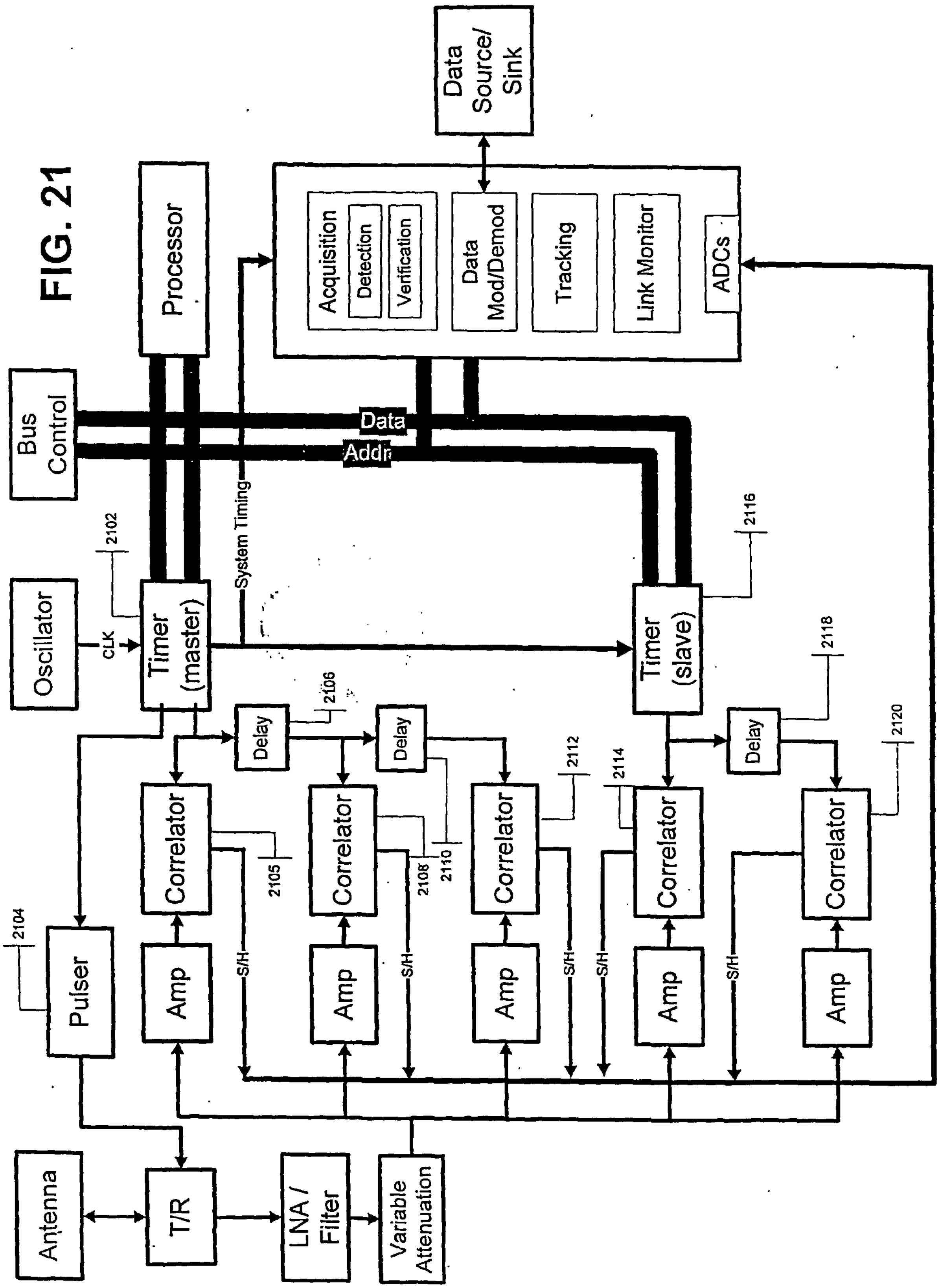

Data Source/ Sink
Processor
Acquisition
Detection
Verification
Data Mod/Demod
Tracking
Link Monitor
ADCs
Bus Control
Data
Addr
System Timing
Oscillator
CLK
Timer (master)
Timer (slave)
2102
2116
2118
2106
2120
2112
2114
2105
2108
2110
2104
Delay
Delay
Delay
Correlator
Correlator
Correlator
Correlator
Correlator
S/H
S/H
S/H
S/H
S/H
Pulser
Amp
Amp
Amp
Amp
Amp
Antenna
T/R
LNA / Filter
Variable Attenuation

FIG. 21